THE STRUCTURE OF EASTERN PAPUA: AN APPROACH VIA GRAVITY AND OTHER GEOPHYSICAL METHODS.

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by

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ABSTRACT

A programme of regional gravity surveys was carried out in eastern Papua in three phases within the period August, 1966 to April, 1968. The area is of interest as an example of a very young orogenic zone and also on account of the large belt of almost undeformed mafic and ultramafic rocks which crops out on the Papuan Peninsula. Aeromagnetic and marine crustal surveys and studies of bathymetry, geology and seismicity were used as controls on the gravity interpretation and together suggest that extensional movements are at present dominant.

Interpretation via computer model studies of the gravity data throws some doubt on the currently popular hypothesis of the ultramafic belt as a thrust sheet of oceanic crust and uppermost mantle, and also on the suggestion that other parts of the Papuan Peninsula consist of ocean floor raised to the surface by simple vertical movements. More conventional mechanisms of intrusion and extrusion seem to be in better accord with the geophysical data.

Computer programs developed for terrain correction of gravity data offer considerable savings in computer time over published methods, possibly at the expense of some loss in accuracy.

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CHAPTER 1

INTRODUCTION

1.1 The Eastern Papua Surveys

Eastern Papua (Figure 1.1) consists of a curved tapering peninsula which extends south-east from the central continental New Guinea block, and a large number of offshore islands. Geologically it forms a link or transition zone between the Australasian continent, of which New Guinea is the active northern margin, and the islands arcs of Melanesia (Figure 1.2); its greatest affinities are with the large islands of New Caledonia and New Zealand with which it is connected by a long, fractured and much distorted rise in the sea floor.

The discussion of the tectonic history and evolution of Eastern Papua presented here is primarily based on the results of regional gravity surveys. The field work was carried out by the author whilst working for the Bureau of Mineral Resources, Geology and Geophysics (B.M.R.), an agency of the Australian Government. The B.M.R. undertakes geological and geophysical surveys throughout Australia, and is also responsible for supervising surveys carried out by private organisations under government subsidy, and for integrating the resulting data. It has a special position in relation to Australian Territories, including New Guinea, where it undertakes some of the work carried out elsewhere by state government geological surveys and mines'departments.

The B.M.R.'s Geophysical Branch includes a gravity section, whose major duties are the routine coverage of Australia with regional gravity surveys and the establishment of a network of accurately known base stations. Rather more than half the mainland area has now been covered by surveys with a station density of one to every 50 square miles,

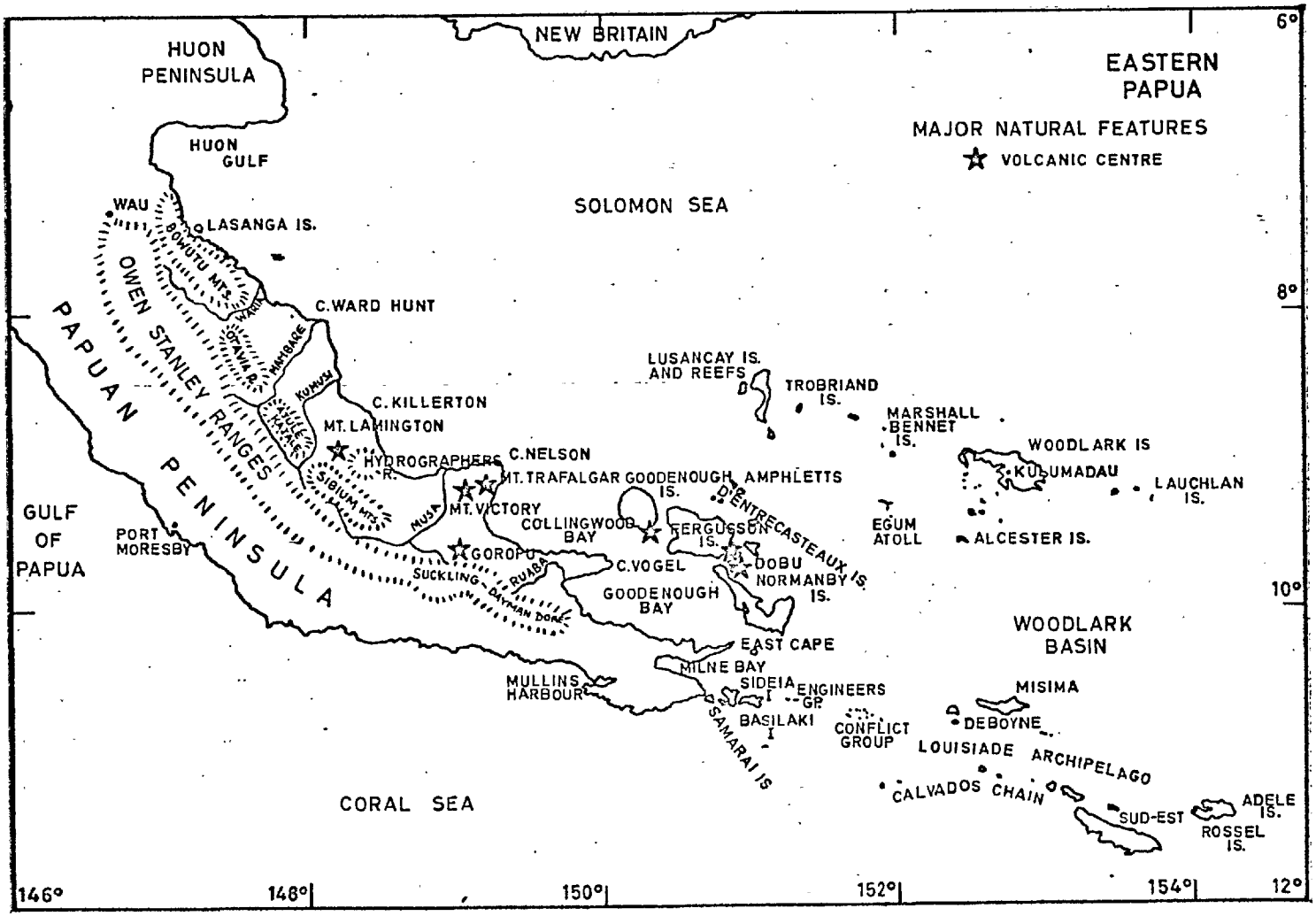


FIGURE 1.1 Eastern Papua; major physiographic features

and this work is now being extended to the continental shelf, the Territory of Papua and the Trust Territory of New Guinea. The two last named areas are administered as a single unit, the Territory of Papua and New Guinea (T.P.N.G.), from Port Moresby, on the south coast of Papua; as well as the eastern half of the island of New Guinea, the territory includes the large islands of Bougainville (which is geographically and geologically a part of the Solomon Chain), New Britain, New Ireland, Manus and countless smaller islands and cays. Most of the land area is mountainous and all of it is densely vegetated. The climate is tropical and the rainfall is high or very high; the weather cycle, particularly in Eastern Papua and the islands, is dominated by the south-east tradewinds.

Systematic geological investigation of Eastern Papua was begun early in the twentieth century, an account of the geology of Papua being published in 1923 (Stanley, 1923). Prior to this time a number of gold rushes, notably to Kulumadau, on Woodlark Island, and to Wau, had resulted in detailed, and usually closely guarded, maps being prepared of a few small areas. During the Second World War a number of airstrips were built, opening up much previously inaccessible country, and after the war the tempo of work increased. In the last five years, the use of helicopters has greatly enhanced the effectiveness of small geological parties, and has made possible the gravity surveys.

The initial gravity work in Eastern Papua was planned as an investigation of the Papuan Ultramafic Belt, an elongated discontinuous feature consisting of large masses of basic and ultrabasic rocks with which very large positive Bouguer and Free-air Anomalies were known to be associated (St John, 1967). Interest in the gravity field of this area had been stimulated by the International Upper Mantle Project, with its emphasis on ultramafic rocks, and also by geodetic studies involving the accurate tracking of artificial satellites; these revealed the existence

of a major geoidal high in the New Guinea-Solomon Islands region (c.f. Woollard and Khan, 1970) and prompted an important series of geophysical investigations by the Hawaii Institute of Geophysics (Rose et al., 1968; Furumoto et al., 1970). The Ultramafic Belt lies in the north-western part of Eastern Papua, and outcrops most prominently in the Bowutu Mountains and the Ajure Kajale and Otavia Ranges, (Figure 1.1), mountain blocks drained by large, fast flowing rivers. It was originallly proposed that all readings should be made on the coast or along these rivers, using jet boats for transport (Figure 1.3), and in fact over a hundred stations were occupied in this way; a further hundred and thirty were established by helicopter (Figure 1.4) in areas not accessible by boat. This work was done in 1966 as an adjunct to geological mapping of the ultramafic rocks (Davies, 1968a). About a quarter of the area covered lies north of the Papuan border, in the Trust Territory of New Guinea.

In the following year a much larger gravity survey was mounted, covering all of Papua east of the 1966 survey area, the easternmost reading being taken on Adele Island (154 24' E, 11 26' S). Pocklington Reef, at 155 45' E, 10 50' S on the same bathymetric rise, is considered to be politically part of the British Solomon Islands and was not included. More than seven hundred gravity stations were occupied in about two hundred hours of helicopter time. In March, 1968, the author again accompanied a geological party and read about two hundred new stations in areas of especial interest. Overall station density is about one to every twenty-five square miles of land area, but varies widely, being as low as one to a hundred square miles in some of the mountain ranges.

Additional gravity data, the equivalent of about a further six hundred stations, is available from shipborne surveys in the surrounding seas, including the Hawaii Institute of Geophysics' Solomon Islands and Solomon Sea investigations referred to above. Other

measurements were made on the Lamont Geological Observatory ship Vema, in the course of work in and around the Coral Sea, (J. Ewing et al., 1970, M. Ewing et al., 1970) and by the U.S.N. Shoup in 1958 and 1959, neither of these sets of results having yet been published. The depth recorder operated on the Shoup was later shown to be unreliable, and in obtaining Bouguer Anomalies the best bathymetry available from other sources has been used. The quality and reliability of the marine data is very variable, but when combined with the onshore observations, a reasonably complete picture of the gravity field of Eastern Papua is obtained. Important gaps remain, notably in dangerous, reef infested inshore waters, and, as noted in Chapter 6, some of the ambiguities in interpretation could be eliminated by surveys in these areas.

Some control on the gravity models used in interpretation is provided by seismic refraction work in the Coral Sea (M. Ewing et al., 1970) and in the Solomon Sea and Woodlark Basin (Furumoto et al., 1970). Further constraints are provided by the seismicity of the area, which has been discussed by Denham (1969). Additional epicentre data quoted in this thesis has been obtained from the International Seismological Centre in Edinburgh.

Magnetic measurements were made on both the Hawaiian and the Lamont Cruises, but the data is still sparse, and no coherent pattern can be identified. Onshore aeromagnetic surveys of the western part of the Papuan Peninsula have been made by the Compagnie General de Geophysique for the B.M.R. (Compagnie General de Geophysique, 1969) and their interpretation is discussed in Chapter 5.

Regional geological mapping of all of Eastern Papua with the exception of the sialic Owen Stanley Mountains has been largely completed, and more detailed work is being done in some areas, both by B.M.R. geologists and by private mining companies. Most of this work is

still unpublished, but much is available in internal records of the B.M.R. These, and in particular the work of I. E. Smith and H. L. Davies, have been drawn on heavily in establishing the geological framework of the gravity studies.

Knowledge of the bathymetry of the surrounding seas is an important adjunct to structural investigations in an area such as Eastern Papua. Krause (1967) has discussed the bathymetry as known from Admiralty charts and from surveys for the routing of the SEACOM cable made by the C.S. Recorder. More recently, additional soundings obtained by H.M.S. Diamantina whilst co-operating with the British Solomon Islands Geological Survey and the Hawaii Institute of Geophysics and, most illuminating of all, the results of semi-detailed surveys by the Royal Australian Navy of parts of the Woodlark Basin have become available. These are discussed in Chapter 5.

1.2 Melanesia

The geological significance of Eastern Papua on anything more than a purely local scale can only be understood if it is considered in its context, that is together with the complex island arcs and restricted marine basins of Melanesia.

The main Melanesian island groups are New Guinea, the Bismarck Archipelago, the Solomons, the New Hebrides, New Caledonia and Fiji (Figure 1.2); for geological completeness the Polynesian archipelagoes of Tonga and New Zealand should perhaps be added to this list. New Guinea itself consists of a central trapezoidal block, attached to and forming the northern margin of the Australasian continent, from which extend peninsulas (the Vogelkop to the west and the Papuan Peninsula to the east) which have some of the characteristics of island arcs. Apart from New Guinea the most characteristically continental of the islands,

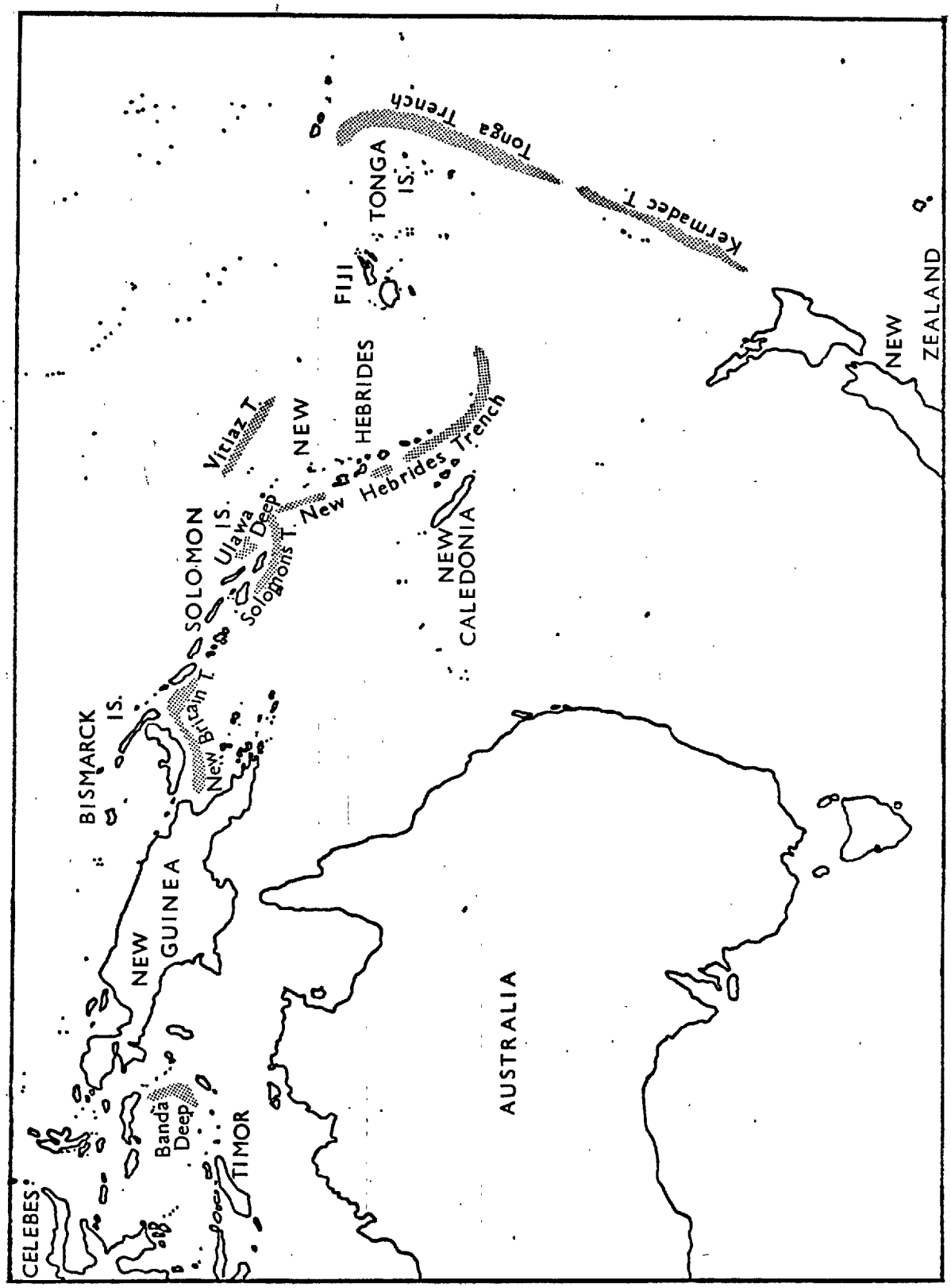


FIGURE 1.2 Melanesia; island groups and trenches.

both in rock type and in crustal thickness, are Viti Levu and Vanua Levu, in the Fiji group. Fiji is also the only part of Melanesia in which ultramafic rocks are not known.

East of Fiji, and extending south as far as New Zealand, runs the very active Tonga-Kermadec Trench (Figure 1.2). Effectively this trench shields Melanesia from direct interaction with the sea floor and underlying lithospheric plate which is spreading west from the East Pacific Rise. In the past it has often been said that the Melanesian arcs and trenches face the "wrong way", that is that the islands lie on the Pacific side of the trenches and that, where these are arcuate, they are convex towards Australia. In view of the shielding effect of the Tonga Trench (to which this comment does not apply) this is one of the least surprising features of Melanesia; in general, the trenches face the active centres of sea floor spreading along the Indian-Antarctic Ridge. The present influence of the Pacific plate is presumably confined to action by shear and drag forces along the northern margin of the area, and in particular along the northern flank of the Solomon Chain. It must be noted however, that this state of affairs may be of comparatively recent origin; it has been suggested (Karig, 1970; Milsom, 1970) that the Tonga-Kermadec crustal sink was formerly located immediately to the east of the Lau-Colville Ridge, at which time the Solomon Islands, and also the New Hebrides, would have been more directly exposed to sea floor spreading from the East Pacific Rise. Comparison of the geology of the New Hebrides and the Solomons, and their very similar bifurcate form, suggests that their tectonic histories have been very closely linked.

The Northern Bismarcks (Manus, New Hanover and New Ireland), the Solomons, the New Hebrides and possibly Fiji, form what may be termed the outer Melanesian chain. A second, inner chain may be tentatively identified; Eastern Papua is characterised by large mafic -

ultramafic sheets and blocks overthrust on sialic geosynclinal sediments, a tectonic style which reappears in New Caledonia,and New Caledonia is in turn strikingly similar to the Northland district of New Zealand (Lillie and Brothers, 1970), particularly in respect of the Lower Mesozoic sedimentary facies and associated fauna. Northland and New Caledonia are linked by the relatively narrow, but certainly continental or subcontinental (Menard, 1970) Norfolk Ridge, and it is also possible to interpret the more complex bathymetry between New Caledonia and New Guinea in terms of a disrupted and rotated extension of this ridge. It has been suggested that both the Norfolk Ridge and the Lord Howe Rise formerly occupied positions marginal to the Australian continent (Carey, 1958), which was therefore presumably the source of the geosynclinal sediments of the inner Melanesian islands, and that both the Tasman Sea and the New Caledonia Basin are the result of subsequent rifting (cf. Cullen, 1970). The Lord Howe Rise may well be the south-eastern section of the Palaeozoic Tasman Geosyncline, the absence of which has been commented on by M. Ewing et al., (1970).

The majority of the rocks exposed in Melanesia are relatively young, and tectonic activity is still widespread. Basement in the larger islands is commonly Jurassic or Cretaceous and many of the smaller islands are apparently entirely post-Miocene. There is widespread evidence of late Mesozoic orogeny (in New Zealand, the Rangitata Orogeny), while the present tectonic phase seems to have been initiated in the mid-Miocene. It is now thought that about 500 km. of movement has taken place along the Alpine Fault in New Zealand since this time (Wellman, 1964). Volcanic activity occurs in all the island groups with the exception of New Caledonia and Fiji.

A further characteristic of all groups, again excepting Fiji, is the presence of large masses of ultra-mafic rock.

Outcrops of peridotite in New Guinea and New Caledonia, and also in the Celebes, immediately west of New Guinea, are among the largest in the world, while Dun Mountain in New Zealand is the type area for the olivine-rich variety, dunite. Petrologically these rocks closely resemble the ultramafics of alpine mountain systems, although their tectonic position is often simpler.

It can be seen from the foregoing that in the Melanesian area most of the fundamental tectonic processes, i.e. island arc and trench activity, transform faulting, alpine-style orogeny, continental accretion and oceanic and continental rifting are occurring or have occurred in relatively recent times. In some cases these processes are seen in very simple form; for example, Tonga-Kermadec, structurally the eastern boundary of Melanesia, is being studied as a type area for the idealised island arc (Isacks, Sykes and Oliver, 1969). In other cases, as with the Hawaii Institute of Geophysics' investigations in the Solomons, it is the very complexity of the area that has aroused interest. In Eastern Papua these two facets of Melanesian geology, simplicity and complexity, occur side by side.

1.3 Eastern Papua

The major topographic features of Eastern Papua are shown in Figure 1.1, while contour maps of the general bathymetry of the area (Figure 5.2) and the detailed bathymetry of the Woodlark Basin (Map 5) also accompany this thesis. The gross structure of the Papuan Peninsula can best be described by reference to three major units, the ultramafic belt, the sialic mountains and the basaltic province; recent unconsolidated and semi-consolidated sediments and Pliocene to Recent volcanics cover large areas, but are unlikely to be important in bulk.



FIGURE 1.3 Jetboat 'Fireball' and LaCoste G.20
Pai-awa River, Territory of New Guinea.



FIGURE 1.4 Helicopter 'CSJ', Bell 47-G3B-1
Iongai village, Papua, 1913 metres a.s.l.

Mountain belts of sialic and of ultramafic rocks run parallel to each other for nearly two hundred kilometres in the north-western part of the Papuan Peninsula. They are separated by a fault trace, the Owen Stanley Fault Zone (Figure 4.3), which is usually marked by a broad intermontane valley; occasionally the zone is narrow and made conspicuous only by a vegetation change. In one or other of these belts occur all the common rock types of alpine mountain chains, the sialic rocks comprising weakly to moderately metamorphosed graywackes and argillites intruded by granodiorites (Dow and Davies, 1964), whilst the ultramafic belt is the equivalent of the so-called ophiolitic suite (Aubouin, 1965). Structural relationships are much simpler than in typical alpine terranes, and it is tempting to see in the young mountains of Eastern Papua a type example of a mountain chain at an early stage in the orogenic process. If this is indeed the case, then studies of Eastern Papua have a bearing on the understanding of the evolution of alpine systems everywhere. However in New Caledonia (Crenn, 1953) and in Cyprus (Gass and Masson-Smith, 1963; Gass, 1968) petrologically similar mafic-ultramafic complexes also occur, probably as overthrusts, and are apparently unrelated to any major orogeny; the possibility that the juxtaposition of the Papuan Ultramafic Belt and a young mountain system is simply coincidental must be admitted.

South of the Owen Stanley Fault and east of 149°, the Papuan Peninsula is built up of a monotonous series of basaltic pillow lavas, with scattered gabbroic intrusions and minor bands of intercalcated limestones (Davies et al., 1968). Petrologically, the basalts are typical low-potassium oceanic tholeiites, and their occurrence in such quantity in the quasi-continental Eastern Papua environment is remarkable. The pattern is further complicated by their being widely intruded by potash-rich syenites.

The Papuan Peninsula continues offshore as the largely submerged Pocklington Rise. The nearer islands along the crest of this rise form part of the basaltic province, but sialic rocks reappear in the Louisiade Archipelago. Along the southern flank the rise plunges steeply into the Coral Sea, while across the Woodlark Basin the northern flank of the Woodlark Rise drops equally smoothly, and still more steeply, into the Solomon Sea. The Woodlark Rise merges with the Papuan Peninsula in the vicinity of Cape Ward Hunt so that the smooth outer slopes of these two rises roughly delimit the area primarily discussed in this thesis. In contrast with the regularity of these boundaries, the bathymetry of the Woodlark Basin between these rises is remarkably complex and provides clear evidence of intensive crustal movements.

The Woodlark Basin is abruptly terminated at its western end by a steep meridional wall capped with coral reef. Two further major offshore units lie west of this wall, one of which, the Cape Vogel Basin, is little known and its structures are only guessed at; it may be simplest to regard the term as a convenient name for the region of generally shallow seas off the north coast of Papua. As the name implies, it is possible that prospective thicknesses of sedimentary rock are developed in some places.

The last major unit, the D'Entrecasteaux Islands, seems to exist as a microcosm of Eastern Papua; virtually every rock type known in the remainder of the area, with the probable exception of the syenites, is found somewhere in the islands. The group's relationship to the mainland, from which it is separated by the deep, steepsided and flat bottomed Goodenough Bay, has long been a subject for controversy, and no simple solution seems in sight.

The problems encountered in studies of Eastern Papua can be broadly divided into two groups, the first including those related purely to the part played by the various structural units in the tectonics of their immediate area and the second to those whose solution, if determined, might be expected to have a bearing on the evolution of similar rock suites and structures elsewhere in the world. Discussion of the origin and subsequent movements of the Papuan Ultramafic Belt would fall into the second group, while questions of past and continuing sea floor movements are likely to be of more local interest. However the present thesis is essentially based on the results of gravity surveys and a rather different approach has been adopted; geological, bathymetric and other geophysical information (Chapters 4 & 5) are introduced mainly to provide controls on the models used in the subsequent gravity discussion (Chapter 6) and the full significance of the deductions made is considered only in the final chapter.

Chapters 2 and 3, which contain discussions of survey and reduction techniques and accuracies, are included in order to establish the degree of validity of the gravity contour maps, and may be omitted by readers primarily interested in the application of these maps to the structural investigation. It is thought that the terrain correction program described in Chapter 3 represents a new approach, chiefly notable for the large savings in machine time that became possible.

CHAPTER 2

THE PRINCIPAL FACTS

2.1 Observed Gravity

All gravity readings in the author's surveys were made using La Coste-Romberg geodetic meter G20. This is a high stability steel spring, thermostatted instrument with a normal drift rate of the order of .01 milligals/day. Reading accuracy, i.e. repeatability of readings taken by an experienced observer, is also .01 mgal. or better; however because of minor irregular variations in calibration factor the value obtained for a given gravity interval may differ by several hundredths of a milligal when different La Coste meters are used, or a La Coste compared with a non-geodetic quartz spring meter. Readings were taken in closed loops or, very rarely, along traverses joining two points of known gravity. In the helicopter work loops were usually closed within less than five hours, but the majority of the boat traverses lasted a full day.

Initially drift was removed by linear interpolation between all base and other repeated readings within a single loop. Most of these loops formed part of an interlocking network, within which values were subsequently adjusted so as to minimize the sum of the squares of the misclosures around closed circuits; a computer program especially developed for the B.M.R. was used (Bellamy and Watterson, 1970). No separate corrections were made for earth tides, although these undoubtedly constitute the major part of the observed drift. In the latitudes of the Eastern Papua Surveys (7° - 12°S) the maximum tidal change over an eight hour period is approximately .15 milligal and the maximum hourly change is about .03 milligals. Since tidal variation is cyclical, with a roughly semi-diurnal period, linear 'drift' corrections are not very satisfactory for the longer

loops, and in the present case result in a maximum adjustment at one station of .16 milligals. This is large in terms of the attainable accuracy of the meter but still small compared to the errors introduced in the reduction process by errors in the other principal facts. In view of this it was felt that, although the network closures could undoubtedly be improved by more rigourous tidal corrections, these could not be justified in terms of the time and effort required.

Absolute values of gravity were obtained by linking the survey at a number of points to the Australian "Isogal" Base Network (Barlow, in preparation). This network is ultimately referred to a value of 979979.0 mgal. for the Melbourne International Base (Potsdam datum) (Dooley et al, 1961) and has also been connected to the International Base at Honiara, in the British Solomon Islands (Milsom, 1971); the 'Isogal' value at this latter station agrees to within a tenth of a milligal with the 'International' value obtained by the Hawaii Institute of Geophysics.

Isogal stations within Eastern Papua are shown in Figure 2.1; these were not in fact established as Isogal stations until after the completion of the 1966 and 1967 surveys, a slightly unusual sequence of events. Ties were made to the future Isogal stations in the course of normal loops and the station values were later incorporated in the least squares adjustment as fixed nodes (i.e. points of known observed gravity). In a few cases Isogal stations were used as bases, and so form natural nodes or link points in the network.

Stations read by V. P. St John and J. Shirley of the University of Tasmania prior to 1966 and not since reoccupied have been incorporated in the anomaly maps (Plates 1 - 4) without further adjustment. Where such stations were reoccupied the differences between new and old values were usually less than half a milligal.

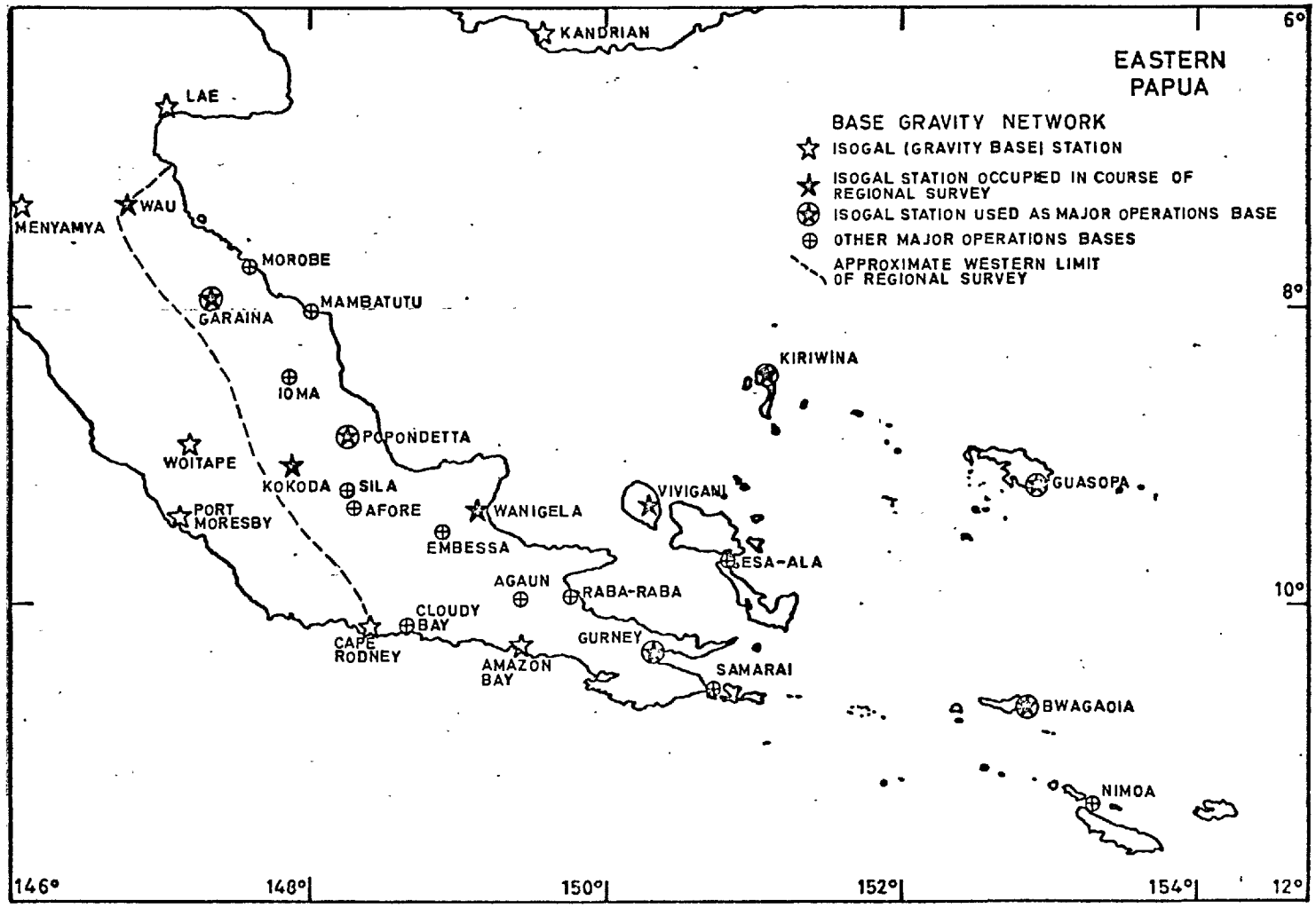


FIGURE 2.1 Eastern Papua; gravity base stations.

2.2 Latitude and Longitude

Navigation on boat traverses was by use of vertical air photos at a nominal scale of 1:50,000 and on helicopter loops over most of the Papuan Peninsula and some of the islands by photomosaics at a scale of 1:63,660 (1 inch to 1 mile). In a few places on the mainland and in most of the island groups 1 inch to 1 mile military maps of World War II vintage were used. Admiralty Charts were used for the scattered minor islets and for Rossel Island. Gravity station locations were recorded in the field by pin-pricking and annotating the navigation sheets.

The gravity data was compiled at a scale of 1:250,000, using U.S. army maps published since 1965 as base references. Some maps have been updated and re-issued by the Australian Army, but unfortunately revisions are generally confined to alterations in spelling of some of the more obscure place names. The accuracy is not high, as comparison with the available photography shows, and in many coastal areas Admiralty Charts were found to be more reliable. For such areas, and for areas not at present covered by the U.S. mapping, bases were prepared by using the Admiralty Charts, occasional 1-inch maps (notably those of Woodlark Island) and compass bearings made by the author. In the case of Rossel Island the Admiralty Charts of the south coast proved to be outstandingly inaccurate and the 'base map' is a sketch made from low level obliques taken from the helicopter with a hand held camera.

Although about half of the survey area was covered by recent vertical photography, no photo centre plots are available, and station positions were transferred to the base maps by reference to topographic features. Since the majority of stations were either coastal or in river beds this did not usually present any great problem. The few stations on ridge crests or at villages were more difficult to locate and

may in rare cases be displaced as much as two kilometres from their true position relative to other features on the map.

The accuracy of plotting of feature on the base maps relative to absolute standards of latitude and longitude is much more difficult to assess. Comparison with photos shows that individual features may be misplaced relative to others by distances of the order of half a kilometre in ten kilometres. Extrapolating this sort of error to the whole of Eastern Papua would lead to the conclusion that some points might be displaced by more than a quarter of a degree. Fortunately such extrapolation is not justified; St John, who accompanied National Mapping teams on the first trigonometric surveys of New Guinea,estimated that latitudes and longitudes scaled off the available mapping were accurate to better than half a minute. This is certainly over-optimistic for the remoter islands, some of which simply do not exist as mapped, and the error estimate should probably be doubled in such areas; it may be taken as a reasonable figure for the Papuan Peninsula.

At a latitude of 10° a change in latitude of one minute (i.e. 1.85 km.) corresponds to a theoretical gravity change of about .4 milligal; changes in longitude have no corresponding effect. Errors in the calculation of gravity anomalies due to errors in latitude are thus not of major importance.

2.3 Height

The heights of roughly half the gravity stations (here referred to as "sea level stations") in the Eastern Papua surveys were obtained by visual reference to actual sea level. These estimates were reduced to a common datum by use of Admiralty Tide Tables, which include tidal stream tables for interpolation of levels from standard ports. For Eastern Papua there are two relevant standards, Dreger Harbour on the Huon

Peninsula for the north coast and Port Moresby for the south coast. Along the south coast the tidal range is of the order of six or seven feet, but along the north coast only about half this.

In addition to errors arising in interpolation (gravity stations being up to five hundred kilometres from the nearest standard port and up to a hundred kilometres from the nearest point for which tidal stream constants are known) there is an unknown error due to a probable difference in datum between Port Moresby and Dreger Harbour. Estimates of the magnitude of this difference could not be made since the tidal pattern changes abruptly at the southern end of the inter-island straits east of the Papuan mainland and each station belongs definitely to one or other of the tidal systems. It seems unlikely that the discrepancy would be more than a metre.

The remainder of the station heights were obtained by using height differences calculated from barometric pressure differences. The theory of this method is developed in Appendix A, where it is shown that, in a dry atmosphere in which temperature decreases with height at a uniform rate (i.e. a constant lapse rate), the height difference H between two points, pressure p_o and p_1 is given by

$$H = r\theta(x - x^2/2 + x^3/3 - x^4/4)/g$$

where $x = (p_1 - p_o)/p_o$, g is the acceleration due to gravity, θ is the mean temperature of the air column between the two points and r is the gas constant per gram. The value for air of this last quantity is rather variable; for the Eastern Papua surveys the international standard value of 287.03 Joules $^{o}K\ gm^{-1}$ was adopted and there seems no reason for assuming that this is significantly in error. A correction has also to be made for humidity (Crone, 1948), the effect being, under Papuan conditions, to increase the height difference by between .6% and 1.2%. Humidity was

measured at base stations only, using wet and dry bulb thermometers.

In the Eastern Papua surveys pressures were measured using "Mechanism" aneroid microbarometers. These instruments can be read to the nearest hundredth of a millibar (equivalent to an elevation change of about 10 cm.) but readings are repeatable only to about five hundredths of a millibar. Absolute readings are not reliable and it is necessary to recalibrate at intervals under laboratory conditions to obtain values of P_o.

The "single base" method of observation was used, the field and base barometers being read simultaneously at the base station at the start and finish of each set of field observations and the base barometer being read at intervals of fifteen or twenty minutes throughout the intervening period. This method is normally satisfactory provided that field observations are not made at more than 30 kilometres from the base station, that there is not a significant pressure gradient between the field station and base, that a number of points of known height are occupied and that not more than two hours elapse between repeat readings at base with the field barometer. Because of the difficulties associated with New Guinea operations all these rules were broken in the Eastern Papua surveys, the most serious obstacle being the lack of usable known heights within the survey area. Only one such point could be occupied, the others being out of range of the barometers (e.g. Mt. Albert Edward) or no longer re-occupiable (e.g. Mt. Lamington). The inland heights are thus built up on height differences from "sea-level" stations.

In one respect barometric levelling is easier in New Guinea than in Australia, since the behaviour of air masses in the tropics is more regular and predictable than in higher latitudes. A typical example of an observed tropical diurnal pressure curve, with a peak at about 0930 and a minimum at about 1600, is shown in Figure 2.2. Although in no case was it possible to observe an entire diurnal curve simultaneously at

two stations, the regularity of these curves allows some general comparisons to be made between those observed at different places on different days. From these comparisons, and from consideration of the closure diagrams for the network of multiply read stations (about 5% of the whole) some important conclusions can be drawn.

Firstly the importance of the sea breeze effect is emphasised. Sea breezes (and the corresponding, but much weaker, land breezes at night) occur because of the differences in thermal capacity and conductivity between land and sea. In day time, because the land surface heats faster than the sea, the temperature of the near-ground air column increases and it expands, resulting in an increase in pressure at all heights above ground level. This upper air excess pressure is relieved by seaward air flow at height, which in turn results in a lowering of sea level onshore pressure relative to the pressure out to sea. A convection circuit is thus set up with a low level wind blowing from the sea. The lowering of pressure at an inland station is at its greatest in mid-afternoon and so tends to emphasize the diurnal minimum; the amplitudes of diurnal pressure curves at low lying inland bases were commonly $4\frac{1}{2}$ to 5 millibars, one millibar or more greater than the average for coastal bases.

The effect of sea-breezes on barometric levelling is well demonstrated by measurements made between the inland base at Embessa, on the Musa River, and the coast. The height difference between Embessa and a "sea level" station, measured at 1024, was calculated to be 38.7 metres using standard reduction formulae, the same interval measured at 1657 being calculated as 51.5 metres, a difference of 12.8 metres. An almost identical discrepancy was obtained in measurements between Wanigela, half a mile inland and 14 metres above sea level, and Embessa; at 0907 the calculated interval between these two stations was 23.5 metres and at 1710, 36 metres.

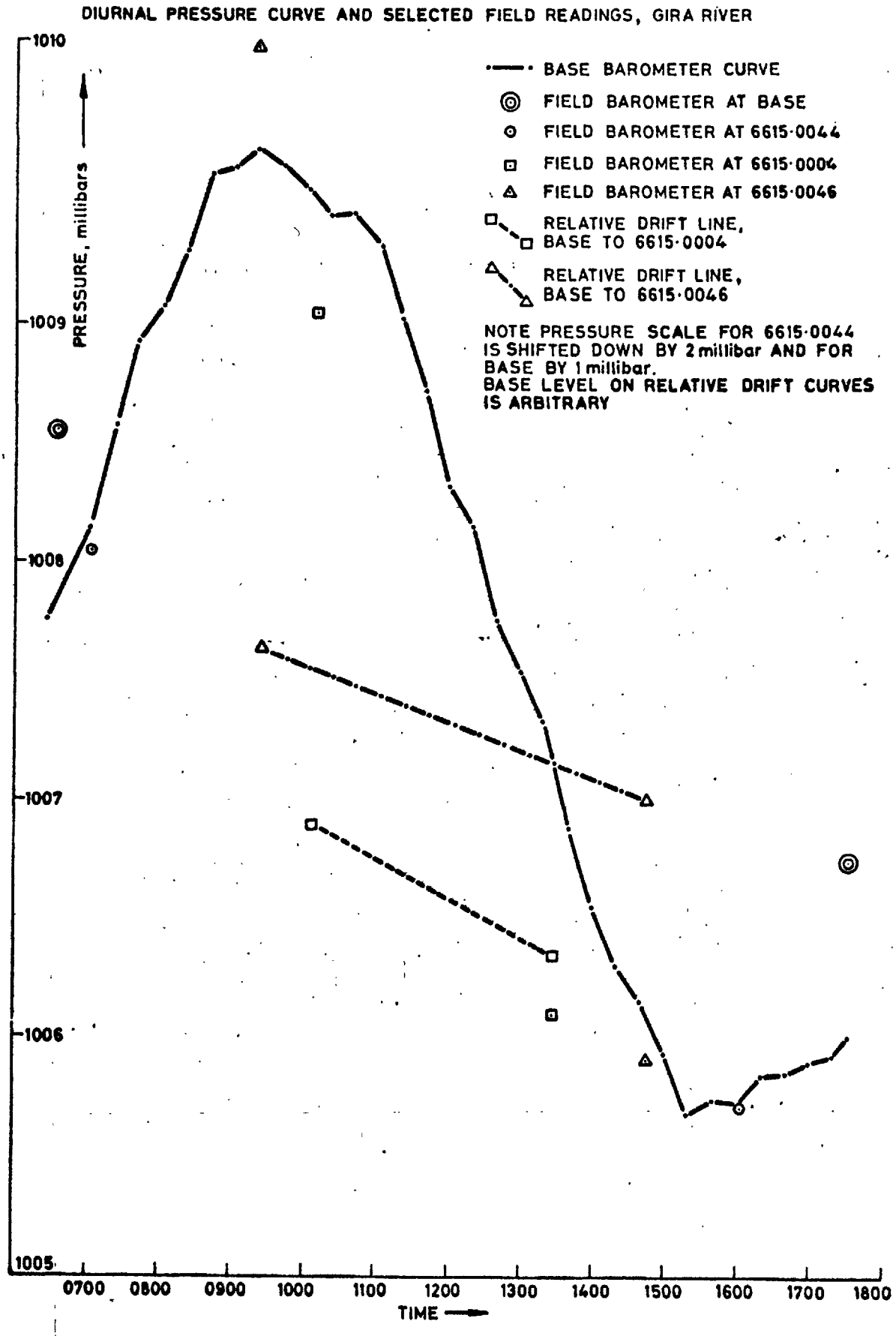


FIGURE 2.2 Typical diurnal barometric curve.

The same effect is illustrated in Figure 2.2, which shows the base barometer curve observed at the Mambatutu coastal base station during the Gira River jet-boat traverse. Also shown are field barometer readings at the two coastal stations 6615.0043 (the Mambatutu base) and 6615.0044 (Gira River mouth) and the two upriver stations 6615.0004 and 6615.0046; each station has been read twice. It is immediately apparent that the field readings at each of the coastal stations differ from the corresponding base barometer reading by an almost constant amount, indicating that the relative drift of the base and field barometers has been negligible. However the readings at the two inland stations have both fallen by about half a millibar in five hours. The same effect, of course, must be occurring at singly read stations along this and other rivers.

Land and sea breezes are well known in meteorology, and a number of theoretical analyses have been made (Haurwitz, 1947; Schmidt, 1947) but despite this there is surprisingly little experimental data published on the accompanying pressure changes. It seems likely, however, that at about 0900 the pressure distribution in the atmosphere over the land and over the sea is approximately the same (Ludlam, pers. comm.) so that barometric levelling involving stations close to a coast should be carried out at or near this time.

A second important effect which is apparent from comparison of the diurnal pressure curves obtained at different bases concerns the relation between temperature observed on the surface and the temperature of the "free" atmosphere. As is shown in Appendix A, if the lapse rate is uniform the mean temperature of the air column may be used without errors in the height calculations; in practice the mean of the temperature readings at the base and field stations is commonly used. As ground temperature usually increases until about 1500 it would be expected that the pressure difference between low and high stations would be a

minimum at that time, implying that the amplitude of the diurnal curve should decrease with altitude.

Comparison of the diurnal curves shows that while this is to some extent so, the effect is much less marked than would be expected from the observed temperatures; in fact, because of sea breezes, the amplitudes of the curves obtained at high inland bases are often greater than those obtained on the coast. The existence of some modifying factor associated with the observed temperatures would also be suspected from the network adjustments. In Eastern Papua, and also in later surveys in the Sepik District of New Guinea (Flavelle, pers. comm.) it was found that smaller misclosures resulted when a constant temperature was used in height calculations than with any form of ground-observed temperature corrections. The reason is made apparent in a number of papers in meteorological journals (c.f. Haurwitz, 1955). Radiosonde and wireline balloon observations show that the temperature variations during the day in a layer perhaps 100 metres thick at ground level are considerably greater than those in the free atmosphere; the amplitude of the diurnal temperature curve at ground level (in Eastern Papua about 7° C at sea level) may be three or four times as great as at a height of 150 metres.

This effect has also been noted in observations made in Ethiopia, for which a mathematical correction system was developed (Crone, 1958). The method involves making a number of assumptions, notably as to the height at which the difference between the air column temperature and the mean diurnal ground temperature falls to 11% of its surface value. This will of course vary throughout the day, from zero to an estimated 1000 ft. and the author himself apparently does not consider it generally practicable; in a later paper 'Notes on Terrestrial Altimetry' (Crone, 1960), he makes no mention of it, merely commenting that

"the temperature required is the temperature of the (fictitious) air column, the length of which represents the difference in height. The observer on the ground is unfavourably placed to determine this and there is some evidence that temperature corrections may sometimes do more harm than good."

The most satisfactory solution, as in the case of the sea breeze effect, would seem to be to carry out barometric levelling at the best time of day, in this case the time at which the region of uniform lapse rate extends to ground level. Published results (e.g. Myers, 1952) show that this occurs at about 0900. (Probably the lapse rate within two metres of the ground is anomalous at all times but it is not difficult to make at least the base temperature readings above this zone. Most base measurements in Eastern Papua were made at about 3 metres above the ground). It will be noted that this is also the time at which the sea-breeze effect is least, a not entirely unexpected result since both are due to the thermal properties of the ground surface.

Although it appears that both problems can be solved by confining observations to the period between eight and ten in the morning, this was not done in Eastern Papua and it is doubtful whether such a restriction could ever be economically feasible on helicopter surveys; the problem of making satisfactory corrections then exists. The method outlined below is very imprecise and subjective and it is felt that now the problems are better understood field procedure can be modified to reduce errors, notably by confining at least those loops which involve coastal ties or large height differences to the most favourable period.

The first stage in the reduction of the Eastern Papua barometric results was to run all data through the standard B.M.R. computer program, which uses the observed base temperatures only and does not correct in any way for variation of temperature with height. The network was then

adjusted by the least squares method already mentioned as used for the observed gravities, with the sea level stations as fixed nodes. After this the network was recomputed using a lapse rate estimated from diurnal temperature curves and field readings; the improvement in misclosures was negligible. However if only values of intervals obtained between 0800 and 1200 were used the improvement was considerable and since, as discussed above, there are sound theoretical reasons for preferring these values, they were accepted. Fortunately there were sufficient such readings taken at all major node points for a valid network to be constructed. As a result some, but not all, of the major discrepancies were removed - for instance the values for the height of Kokoda airstrip obtained from ties to Ioma and Popondetta, formerly differing by about twelve metres, were found to be almost coincident. Although a number of large discrepancies remained, in no case were mis-ties worsened by this approach. The next step was to alter the temperature used at all inland stations by assuming a diurnal variation of roughly one third of that observed at the base station. Intervals between network node points obtained on this assumption were usually within three metres of the values obtained using only morning readings.

Mean height values obtained for the nodal points as outlined above were accepted and used in correcting the heights of singly read stations. Corrections were made in three stages - firstly a correction based on the adjusted values at the nodal points, secondly a correction made by altering the temperature to a value estimated to be appropriate for the entire air column and thirdly, a correction to allow for the sea breeze effect. Of these the first could be made with a fair degree of confidence, no assumptions having been made except as to the greater reliability of mid-morning measurements.

The first adjustment includes the temperature and sea-breeze corrections in-so-far as these factors affect both the nodal station and the field station. Except on flights or boat traverses which involved long periods between node readings the additional correction for temperature deviations was very small, but the sea-breeze correction could unfortunately still be quite large and had to be made entirely empirically. Factors considered were the time of day, the temperature, and the distance of the station and the base from the coast, and from these and the known effects at certain nodes a very rough adjustment was made. The only defence that can be offered for this procedure is that, since in all cases where its existence could be checked, the sea breeze effect was found to exist, calculations assuming its presence are unlikely to be more in error than those that ignore it.

Least squares adjustment of the network of the original B.M.R. program resulted in a standard deviation of about five metres for multiply read stations, with a maximum adjustment of fifteen metres. However the effects described above caused these results to be systematically in error, most heights being too great. Because of the intuitive nature of some of the further corrections made, the concept of standard deviation around the network does not have any real meaning, and it is claimed only that the standard deviation is not increased, and that some sources of systematic error have been removed. Height errors of up to twenty metres probably still exist in some areas and an estimate of standard deviation of five metres (equivalent to one milligal in Bouguer anomaly) seems reasonable. It is worth noting that the only positively known height occupied, the third order trig. station AA 029 on Cape Vogel, 337.3 metres above sea level, was estimated barometrically with an error of a little over a metre. Errors due to faulty height estimates will be much reduced in areas of low relief, and correspondingly more reliance may

be placed on contours of gravity anomaly in such areas.

2.4 Marine Data

The marine measurements discussed in this thesis were all made aboard moving surface ships (Figure 3.4). In measurements of this type it is important not only that the gravimeter be working satisfactorily, but also that the ship's course, speed and position are accurately known. These data are all required before a quantity analogous to the observed gravity of land stations can be calculated. The ship's position is also required for the calculation of the theoretical ('normal') gravity and since all measurements are made on the same level surface (ignoring tidal variations) the difference between these two quantities gives the free air anomaly directly. The water depth immediately below the ship is required for the later stages of the reduction process but, as will be shown in the next chapter, the quantity is of less fundamental importance than is height in the case of land stations.

The marine gravity data was taken from three different sources and originally obtained in as many different forms. The surveys carried out by the U.S.N. Shoup in 1958 were the earliest and probably the least reliable; apart from the fact that considerable improvements have since been made in marine gravimeters, the U.S. Navy itself admits that the ship's echo sounder was not working, which does not inspire confidence in the remainder of its apparatus. For the principal facts catalogue a depth value was obtained using the best bathymetry available from other sources. Gravity values were obtained as free air anomalies from plotting sheets at a scale of 1:250,000, latitude and longitude values being scaled off the same sheets. Estimation of the accuracy of the Shoup's results is almost impossible, but occasional errors in excess of fifty milligals would not be surprising.

Free air anomalies obtained aboard H.M.S. Dampier by the Hawaii Institute of Geophysics in 1965, together with the appropriate latitudes, longitudes and depths, were also taken from plotting sheets. Errors in this data are discussed at length by Rose et al., (1968), who conclude that most errors would result from ship navigation problems rather than gravimeter observation errors. The gravity features revealed by their work probably exist, to within a standard deviation of five milligals, but may be significantly misplotted.

These comments, and the very rough error estimate, can probably be applied to the Lamont Observatory/University of New South Wales data obtained aboard "Vema" in 1968. This data was supplied in the form of a computer printout listing observed gravity as well as free air anomaly, latitude and longitude, simple Bouguer anomaly and Eotvos correction. Again it seems (M. Ewing, pers. comm.) that there were navigational problems which are likely to be of greater importance than errors in actual gravity measurement. Where ship tracks from the Lamont and Hawaii cruises intersect differences between estimates of observed gravity range from ten to fifty milligals. However in the main these discrepancies can be removed by assuming navigation errors of the order of five to ten nautical miles.

CHAPTER 3

GRAVITY REDUCTION AND INTERPRETATION

3.1 The reduction of gravity data

The major part of this thesis is concerned with the reduction and interpretation of gravity data collected by the author in Eastern Papua and by various oceanographic expeditions in the surrounding seas. The area is one of extreme topographic and bathymetric relief, with which are coupled large lateral density variations, and in such an area the nature of the reductions used assumes an added importance. Since, despite the long history of gravity surveys, confusion still arises over the use of some of the commonest terms, a short discussion of the theoretical basis of the reductions used seems appropriate.

TABLE 3.1

REDUCTIONS APPLIED TO OBSERVED GRAVITY VALUES

SIGN	QUANTITY	ANOMALY
-	Latitude correction (normal gravity)	
+	Free Air Correction	Free Air Anomaly
-	[1,2] Bouguer Correction	Simple Bouguer Anomaly
+	[1,3] Terrain Correction	Extended Bouguer Anomaly
+	[2] Isostatic Correction	Isostatic Anomaly
±	Geological Corrections	

NOTES
1. Sometimes combined in a single (±) topographic correction
2. Sign reversed for marine corrections
3. Sign variable for marine corrections

Gravity reductions are attempts to remove or reduce the effect on gravity observations of causes not of immediate geological interest. All reductions are to some extent interpretative, since the anomaly calculated is a measure of the deviation of the actual gravity field from that due to some idealised model; this is true even of the simple latitude correction which, as discussed below, is based on a conventionally adopted ellipsoid. Errors in gravity anomalies, then, may be said to exist at two levels; there are errors in the reductions due to inaccuracies in parameters used, and there are deviations of the chosen model from reality. In conformity with normal practice, use of the term "errors" will here be confined to the first of these groups, but it must be remembered that it is only safe, or even possible, to do so if the model being used is clearly defined and understood.

In this chapter the quantities and corrections listed in Table 11 are discussed and estimates of the errors in measurement of each in Eastern Papua are given. These estimates, unless otherwise stated, are 'probable errors'; of a given set of values half will be in error by more than these amounts, half by less. This is here preferred to the more usual 'standard error' (standard deviation, root mean square error), as use of the latter implies an analytical rigour which, because of the practical difficulties referred to, is unfortunately not in this case attainable. For a normal (Gaussian) error distribution the probable error is approximately two-thirds of the standard error.

As noted in the previous chapter, observed gravities in Eastern Papua are closely tied to the Australian 'Isogal' network; they are unlikely to be in error, with respect to this system, by more than a quarter of a milligal, and the probable error is estimated at .1 milligal.

The latitude correction is applied to remove the effect of the earth's ellipticity. At the surface of a uniform, biaxial

ellipsoidal earth the gravity field would be given by an equation of the form

$$g = g_o (1 + a \sin^2 \phi + b \sin^2 2\phi)$$

where g_o is the equatorial gravity, ϕ the latitude and a and b are constants. Latitude corrections in Eastern Papua, in common with virtually all other regional gravity surveys, have been made using the 1930 International Gravity Formula.

$$g = 978049 (1 + .0052884 \sin^2\phi - .0000059 \sin^2 2\phi) \text{ milligals}$$

This formula is consistent with the Potsdam system to which the observed gravities are ultimately referred, so that the error in the Potsdam datum, believed to be about 15 milligals (Woollard, 1969), is removed with the latitude effect and is not transmitted to the later reduction stages. Universal use of the 1930 formula has been of prime importance in allowing direct comparison between gravity surveys made in different areas. Although based on a reference ellipsoid which is now known to be inaccurate, change would be pointless at present since the best fitting earth ellipsoid cannot be determined until the whole of the earth's surface has been covered by regional gravity surveys.

It has been proposed (O'Keefe and Kaula, 1964) that instead of referring gravity measurements to the real earth, the hydrostatic figure be used, thus relating the anomalies more directly to the existing state of stress. An additional advantage would be that, since the hydrostatic figure is largely based on theoretical considerations and relies less on a world wide network of gravity observations, it could be defined to a sufficient accuracy within the next few years. The practical difference between the two formulae when applied to a limited survey area is small, the relative change in normal gravity between the

northernmost and southernmost stations in Eastern Papua being less than one milligal, but it is worth noting that the absolute values on the anomaly maps (Maps 1 - 4) would have been increased by about ten milligals if the hydrostatic reference figure had been used (Khan, 1968).

With the exception of a few stations on the outer islands, the probable latitude errors in Eastern Papua are estimated at $\pm$ .2 minutes. This corresponds to a probable error in gravity reduction of .1 milligal.

The free-air correction is made to compensate for variations in the distance of the gravity stations from the earth's centre; in practice sea level is taken as the reference surface approximating to the geoid (the equipotential surface at mean sea level) and the height of the station above or below this level is used in the calculations. The effect of topographic masses is ignored and individual Free-air Anomalies are thus strongly dependent on elevation. However if the topography is isostatically compensated, i.e. if there is no net mass excess or defiency in the earth's uppermost layers, the integral of Free-air Anomaly over a sufficiently large area is zero.

The derivation of the free air correction, g_f, is given by Heiskanen and Vening Meinesz (1958, p. 148), who show that

$$g_f = 2 \frac{g_m}{r} h \left(1 - \frac{3}{2} \frac{h}{r} \ldots.\right)$$

where g_m is the force of gravity halfway between the point of observation and sea level and r is the local radius of the earth. The second term in the equation is almost negligible, being less than .1 milligal at 1000 metres and .3 milligal at 2000 metres, but in the calculations for Eastern Papua the full expression was used; a number of the stations are more than 2000 metres above sea level and the additional computer time involved is negligible. There is no detectable effect on the smoothed Free-air

Anomaly map (Map 1).

A more important question concerns the application of terrain corrections to Free-air Anomalies and the related difficulties raised by local changes in earth curvature. Whether or not a terrain correction should be applied depends entirely on the definition of Free-air Anomaly adopted, but since the anomaly maps are normally used to investigate the state of stress in the earth, it may be thought desirable that the integral over a wide area in which isostatic equilibrium prevails should be zero. As has been pointed out by StJohn (1967), for this to be true a correction must be applied for the effect of the topographic masses above the level of the station, as these masses lie outside the closed surface to which Green's theorem may be applied. In addition they may be compensated isostatically by mass deficiencies at depth and since in this case both the excess and deficit masses affect the gravity field at the station in the same sense, the combined effect may be quite large. StJohn felt able to ignore this problem since many of his stations were on mountain peaks and the remainder in broad valleys where terrain effects were negligible; valleys below the level of the station do not, of course, necessitate a terrain correction to the Free-air Anomaly on any system since both the mass deficit and any compensation at depth lie within the Green's theorem surface. The situation is rather different in the author's surveys, where many stations lay at the bottom of narrow river valleys, and a terrain correction has been calculated, assuming Airy type isostatic compensation (see below) of the external topography. The effect of the correction is to increase the value of the Free-air Anomaly computed for low-lying stations in mountainous areas, and thus to reduce to some extent the very steep gradients normally associated with the unsmoothed anomalies. The correction seems valid in terms of the requirement of zero free-air integral in stable areas, but individual values may differ markedly from those of

Free-air Anomaly as normally obtained.

The concept of the Free-air Anomaly is further complicated by consideration of the effect of near-surface mass distributions on the parameters in the equation given. The mean value of the earth's radius is usually used for r, although the actual radius at the latitude of the observation has been used in some cases; the effective difference is negligible except for very high stations. It has, however, been argued (de Graaff-Hunter, 1951) that the earth's radius of curvature should be used instead. This is equivalent to relating the Free-air Anomaly to the 'actual' geoid and assuming that this is parallel to the equipotential through the point of observation. In Eastern Papua, where there are both large elevation changes and large changes in upper crustal density, the difference may be more than ten milligals. The weakness of the arguments for the use of the radius of curvature in free-air corrections lies in the impossibility of determining this quantity in areas where its variations are likely to be important. Extreme local changes of curvature are the result of unknown local mass distributions whose effect can only be measured at points on the physical surface of the earth and cannot be reliably extrapolated to a geoid below that surface. De Graaff-Hunter admits that accurate and detailed measurements of earth curvature are almost impossible and finds it necessary to use a curvature averaged over a wide area surrounding the station - a procedure he does not attempt to justify. Radius of curvature reductions have been used in the past by only a few geodesists and now appear to have been generally abandoned. In this thesis the value of r appropriate to the International Reference Ellipsoid at the latitude of observation is used, relating the Free-air Anomaly directly to the theoretical gravity obtained from the 1930 formula.

Errors in Free-air Anomaly arise from inaccuracies in the measurement of both gravity and station height; the first of these sources can be safely ignored in comparison with the second. The probable error in elevation of stations not at sea-level is, as shown in the previous chapter, of the order of three metres, corresponding to a probable error of approximately one milligal in free-air correction.

An additional probable error of about half a milligal is introduced if terrain corrections are applied. Errors are highly dependent on station location, and quoting an overall probable error for the entire survey is a rather misleading, although convenient, procedure; in fact they may be more than doubled in rugged terrain and be close to zero in coastal districts and on most of the outer islands. This is true not only for the Free-air Anomalies but also for the Bouguer and Isostatic Anomalies discussed below.

Even in a region in a state of complete isostatic equilibrium the gravitational effects of the topographic masses and their compensation at depth do not cancel for surface observations, although this condition may be approached in extensive plateau areas. The inverse square law and directional effects ensure that the field due to large surface masses is dominant near the gravity station and that the compensation becomes relatively more important as distance increases; in this respect the most effective part of the topography is that which lies directly between the geoid and the gravity station. The higher the station the greater the mass involved, so that Free-air Anomalies are extremely sensitive to changes in height and gradients are large and unrelated to changes in underlying geologic structure. Accordingly it is normal practice to smooth Free-air Anomalies prior to contouring, the cut-off value of the smoothing filter being usually determined by the 'wavelength' of the topography.

The Free-air Anomaly map of Eastern Papua (Map 1) is based on a topographic wavelength of half a degree of latitude (about 55 km); the smoothing filter uses the sinc function (Bracewell, 1965), given by the equation

$$\text{sinc } x = \sin(\pi x)/\pi x$$

as a weighting factor, operating on all Free-air Anomaly values within 165 km of the point of calculation. It must be noted that a perfect smoothing filter should not introduce errors, although, as in any averaging process, some of the initial information is lost, but that if the distribution of observation points is irregular, aliasing errors may be introduced; they are probably present in the smoothed anomaly map of Eastern Papua even in parts of the onshore area, and are certainly present in the offshore sections. For the mainland the error in this map is estimated at about two and a half milligals.

The Bouguer Anomaly was developed by Bouguer (1888) as a simple correction for the effect of the rock masses lying between the point of observation and the reference surface. As noted above, these masses are the primary cause of the very high gradients observed in unsmoothed Free-air Anomalies. For a wide range of topography the gravitational effect of the Bouguer model, an infinite horizontal slab of uniform density, is quite close to reality, as can be demonstrated by some simple calculations.

Firstly it can be shown that the gravitational effect of a cylindrical ring element at any axial point, distant h and H (h<H) from the planes limiting the ring, is given by

$$g = 2\pi G\rho \{(H^2 + R^2)^{\frac{1}{2}} - (H^2 + r^2)^{\frac{1}{2}} - (h^2+R^2)^{\frac{1}{2}} + (h^2+r^2)^{\frac{1}{2}}\}$$

where G is the gravitational constant, ρ the density of the ring and r and

R the inner and outer radii respectively. This equation is true whether h and H are measured in the same direction or not, since the effect at the origin of the element from -h to +h is always zero

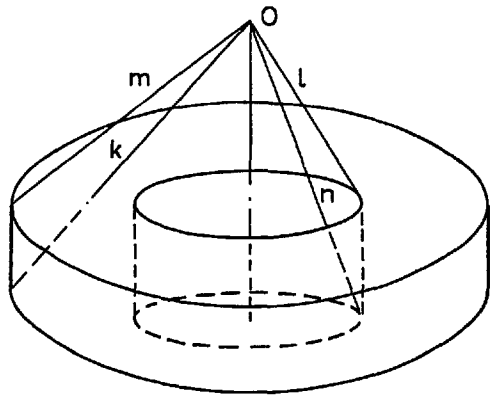


FIGURE 3.1

With the notation in Figure 3.1 above the equation may be rewritten

$$g = 2\pi G\rho \ (k + l - m - n)$$

For the Bouguer plate both r and h are zero, and the difference between $(R^2 + H^2)^{\frac{1}{2}}$ and R approaches zero as R approaches infinity, giving the simple formula

$$g_b = 2\pi\rho GH$$

An idea of the effect of deviations of the terrain from the Bouguer Plate can be obtained by comparing this expression with the field at the centre of the upper surface of a finite disc. If the ratio R/H is 50, g/g_b is .99, if 10, .95, if 5, .9 and when R equals H, g/g_b is .58. Since g_b is itself directly proportional to H, the difference in milligals between g and g_b increases rapidly with increase in the height of the block, for constant radius.

The model used above is, of course, far from realistic, and in particular makes it easy to forget that topographic relief is just

as significant above the station as below it. Since masses above station level and mass deficits below both result in a reduction of field at the station, corrections for deviation of the topography from the Bouguer Plate are always positive and never cancel. It is quite useful to compare the field due to a right circular cone at its own apex (Figure 3.2) with g_b, remembering the results can be applied either to a station at the top of a conical hill or at the bottom of a conical depression.

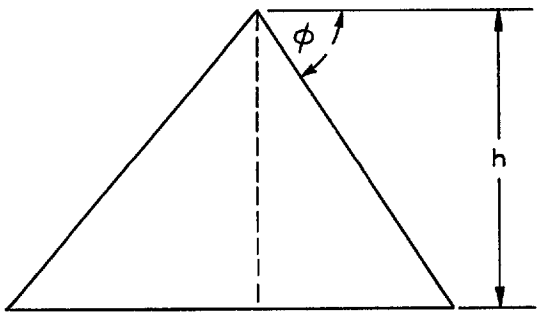


FIGURE 3.2

The field at the apex due to the lamina of thickness dh is dg.

$$dg = 2\pi G\rho((h + dh) - h - l + n)$$

now $l - n = dh \sin\phi$, so

$$dg = 2\pi G\rho (1 - \sin\phi)\, dh$$ and integrating

$$g = 2\pi G\rho (1 - \sin\phi)$$

Substituting, we find that if ϕ is 35', $g/g_b = .99$, if 2° 50', .95, if 5° 25', .9 and if ϕ is 25°, $g/g_b = .58$. Numerically, of course, the difference is again proportional to h.

In regions of low relief the simple Bouguer correction provides a satisfactory approximation to the effects of elevation and topography, provided only that an appropriate density is used. If this is

not done the resulting Bouguer Anomalies will still be markedly dependent on elevation, Nettleton's method of determining the bulk density of near surface rocks (Nettleton, 1940, p. 57) being based on this fact. (It should be noted that Nettleton's method is of very limited application in Eastern Papua, depending as it does on the assumption that there is no correlation between rock density and topography). Simple Bouguer Anomaly maps based on an unsuitable value of density lose much of their usefulness, particularly if there are large elevation differences or large lateral density variations present, but do serve one important purpose. Since the Simple Bouguer Anomaly is derived solely from an assumed and constant density and from the four principle facts (latitude, longitude, height and observed gravity) of the gravity station, the original data is in principle recoverable from the anomaly map. This will not be the case if further assumptions and corrections are introduced. Useful reinterpretations have often been made based on Simple Bouguer Anomaly maps when the original data has been lost or destroyed and, while it is to be hoped that such instances will be less common in the future, the production and wide circulation of such maps still represents an important safeguard. Accordingly a map has been produced to accompany this thesis using the standard density of 2.67 gms/cc (Map 2), which has already been adopted in a number of adjacent areas (c.f. Laudon, 1968). Errors here arise solely from errors in the principal facts and the probable error is estimated to be about two milligals.

The 'Extended' Bouguer Anomaly is obtained by correcting for deviations of the actual land surface from the Bouguer plane and a vast amount of additional topographic information must be used. Selection of this data, whether by approximating contour lines by polygons or by estimation of the average height of topographic blocks, is at least partly subjective, and it seems much less reasonable, once this element is

introduced, to cling to a uniform density where this is not appropriate. Accordingly the Extended (terrain corrected) Bouguer Anomalies shown in Map 3 have been calculated using variable density. No density measurements were made on hand specimens collected in Eastern Papua, since helicopter loading precluded collection of samples of suitable size and since the densities of a few surface samples are in any event unlikely to be truly representative of the bulk densities of the underlying rock masses; instead Nettleton's method was applied in the few places where it was likely to be valid, and averages of published bulk densities from other parts of the south-west Pacific (StJohn, 1967; Robertson, 1967; Hatherton and Leopard, 1964) were used for the remainder.

The degree of interpretation involved in preparation of the Extended Bouguer Anomaly map is much greater than for the uncorrected anomalies and the errors introduced are accordingly greater; the total probable error is estimated at about five milligals. At first sight it seems that making corrections has reduced accuracy, but the use to be made of the maps must always be borne in mind; if terrain corrections are not made at this stage they will have to be made, much less conveniently and probably with less accuracy, during interpretation.

Although the main purpose of the Bouguer and, more particularly, the Extended Bouguer, correction is to reduce the dependence of the contours on station elevation, it must be realised that, because of density variations in the superficial crustal layers, this can never be done completely. The reason for this is illustrated in Figure 3.3 overleaf.

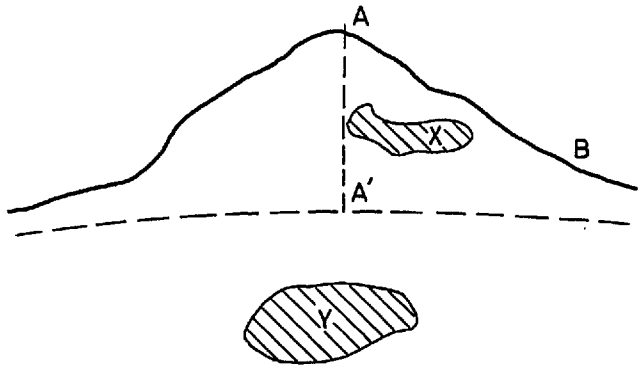


FIGURE 3.3

The Extended Bouguer Anomaly relates the gravity observations at A and B after removal of the effects of the topography above the geoid; the mass inhomogeneity X, if not included in these calculations, represents a source of error. However, masses such as Y, below the reference level, are not considered in the reduction calculations and their effect forms a valid part of the computed anomaly. Clearly the field due to Y at A will be different from the field at B, and, also from the field at the point A'(which cannot of course be occupied) on the reference surface. It follows that it can never be true to say that the Extended Bouguer, or any other, anomaly represents a reduction to the reference level. The elevation of the point of observation cannot be altered by any reduction process, and where this is likely to be an important factor it must be allowed for in interpretation.

If either station height or topographic relief is large, topographic effects may be significant out to a distance at which the 'flat earth' approximation (implicit in the Bouguer assumption) is no longer valid. Corrections for earth curvature are less conceptually simple than might appear at first sight; carried to a logical conclusion terrain corrections would have to be extended around the whole earth and be applied to the theoretical field of a spherical shell, twice the field of a Bouguer plate of the same thickness. However a shell with thickness

equal to the station height would be a very poor approximation to reality, firstly because the mean elevation of the earth's surface is very close to zero and secondly because most deviations from zero level are compensated by mass changes at depth. For distant points the effects of surface irregularities and their compensation are very nearly equal. Maps of the combined effect of topography and its assumed isostatic compensation at all points on the globe are published by the Isostatic Institute of the International Association of Geodesy (Kärki, et al., 1961). These maps ignore all topographic-isostatic effects from sources within 166.7 km of the observation point (i.e. $1\frac{1}{2}^{o}$ of latitude, the outer radius of the Hayford zone O) and are based on the assumption that topographic changes are compensated by changes in the depth of a major density discontinuity at about 30 km below the geoid (the Airy isostatic assumption). For these distant corrections the exact nature of the isostatic model used is not very important.

The I.A.G. field is quite a significant factor in Eastern Papua, varying from ten to twenty-seven milligals from west to east across the area. Although this field is probably itself in error by a milligal or so, it has been subtracted from the Extended Bouguer Anomalies in Map 3; these are the anomalies chiefly used in interpretation of the local structure (Chapter 6) and it seemed desirable that as far as possible effects due to sources outside the immediate area of interest be removed.

The Isostatic Anomaly represents an attempt to allow for the effect of compensation of the local as well as the distant topography. The masses considered are only a few tens of kilometres from the point of calculation and the vector of their gravitational attraction makes only a small angle with the direction of the earth's main gravitational field. Under these conditions the value of the correction is critically dependent on the nature of the isostatic model used. Two main classes of assumption

have been made, the continuous (Pratt) and the discontinuous (Airy), but the discovery of the Mohorovicic seismic velocity discontinuity (Moho), and its identification as the boundary between the earth's crust and mantle, led at one time to the virtual abandonment of the Pratt model. Early observations of seismicity showed a strong correlation between topographic height and depth to Moho, and, since the marked increase in velocity almost certainly indicates a marked density increase, the Airy model seemed to be proven correct. More recently seismic refraction studies have directed attention towards the variations in mantle velocity at the Moho. Woollard (1968) has shown that for the continental United States a simple relation between surface elevation and crustal thickness can be established only where the mantle velocity lies in the range 8.0 to 8.2 km/sec. In other areas a correlation is observed between thin crust, crustal uplift, and low mantle velocity, implying reduction in mantle density; possibly a transfer of mass between crust and upper mantle may be a second important mechanism for maintaining isostatic equilibrium. In some cases the compensation approaches that proposed by Pratt, with the topographic mass supported by a density deficiency throughout an extended column.

As yet there have been no determinations of mantle velocity made on the Papuan Peninsula, but a number made around the Solomon Islands (Furumoto et al., 1969) show variations from a low of 7.3 km/sec near the Pocklington Rise to a high of 8.5 km/sec on the Solomons' Plateau, east of the islands. Velocities along strike from the Papuan Peninsula are all abnormally low (i.e. less than 8.0 km/sec). This suggests, by analogy with the North American observations, that isostatic adjustments in Eastern Papua are not made only by lowering of the Moho.

A further weakness of the conventional Isostatic Anomaly is that no allowance is made for the compensation of mass excesses or deficiencies present in the upper crust. The distribution of such

variations is seldom well enough known for corrections of this sort to be practicable, even if the computation time involved were not prohibitive, and as a result Isostatic Anomalies are of very limited use in areas of strong density contrasts. In Eastern Papua the isostatic map (Map 4) may have some validity in the Owen Stanley Ranges, and possible also in the basaltic areas, but is almost meaningless along the Papuan Ultramafic Belt. Because of this limited usefulness, only a single, Airy, anomaly has been calculated. To save computation time it has been assumed that an inner topographic disc of radius 55 km is compensated as a single block; the difference between this anomaly and that calculated on the assumption of the most exact of local compensation is unlikely to excede one milligal. The errors in the Isostatic Anomaly are those associated with the Extended Bouguer Anomaly plus an error due to imperfect knowledge of the shape and density of the topography being compensated. An additional probable error sum of two milligals is assigned to this cause, giving a total probable error of seven milligals.

Corrections for sea-surface observations; in the discussion above it has been assumed that the gravity observations are made at ground level. However a large number of gravity measurements are now made on surface ships and some results of this type are incorporated in the present thesis (Figure 3.4). In one respect these readings are easier to handle than those made on land, since, after instrumental and acceleration corrections have been made, the Free Air Anomaly is obtained directly by application of the latitude correction. However in shallow water these Free Air Anomalies are critically dependent on bottom topography and a number of so called Bouguer reductions have been proposed to reduce or eliminate this effect. Most involve 'replacing' the sea layer with that of an equivalent volume of rock of some specified density, the actual density chosen being the subject of some controversy. Perhaps the

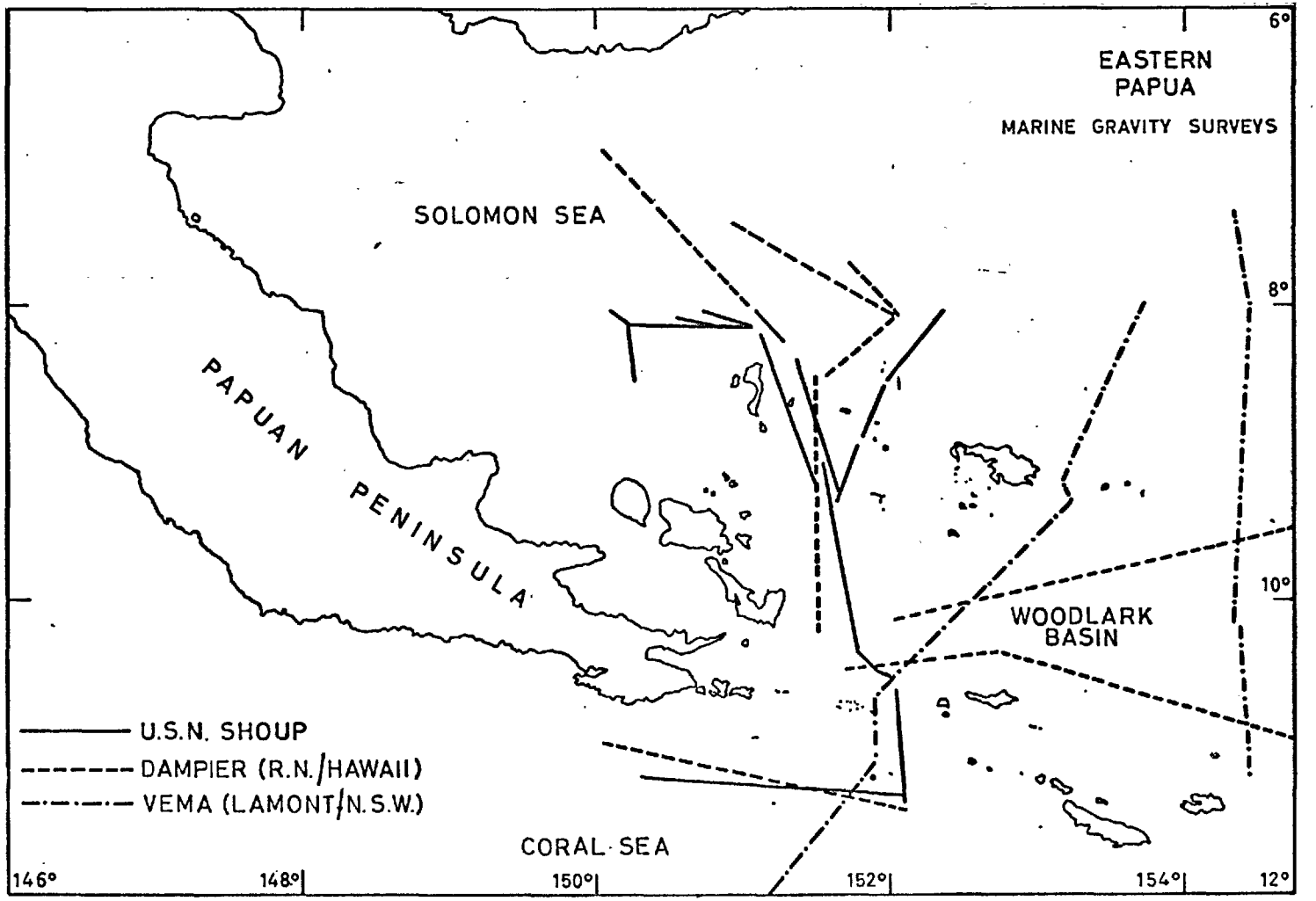


FIGURE 3.4 Eastern Papua; marine gravity surveys.

commonest assumption is the use of the mean upper crustal rock density, 2.67 gm/c.c. Other authors prefer a mean sea floor basalt density, usually in the vicinity of 2.8 gms/c.c. Rose et al., (1968) use a basaltic density varying with depth, a procedure that seems invalid at least in areas such as Eastern Papua; the density of marine basalts is dependent on the depth of extrusion, and this may be vastly different from the depth of the rocks at the present time.

Since the mass deficiency of the sea water is compensated wholly or in part by a rise in level of the Moho, 'infilling' of the sea with material of higher density results in Bouguer anomalies which are strongly positive. The true nature of the marine Bouguer correction has been discussed by Vajk (1964), who proposes a new type of reduction which he calls the 'modified free air anomaly'. Essentially this is an anomaly calculated with reference to sea level for land stations and to a standard sea floor in the oceans. Corrections are made only for deviations from these conditions, assumptions being made as to the bulk density of bathymetric features. The major deviation is represented by the continental margins and in such areas Vajk fits a model continental margin to the observed bathymetry and removes from this the effect of sea bed relief. Unfortunately, as has been shown by a multitude of seismic refraction measurements (c.f. Drake, 1966),continental margins are rarely simple structures and the essentially two dimensional approach used by Vajk can seldom be applicable. This is particularly true of active tectonic areas such as the New Guinea-Solomon Islands region.

A more profitable approach is to consider the use that will be made of the calculated anomalies. In general an attempt will ultimately be made to fit a geological model to the gravity contours or profiles. Such models are of necessity extremely simple and it is virtually impossible to allow, at this stage, for complex bathymetry,

although it may materially affect the gravity field. This means that, as is the case with normal onshore stations, the terrain correction must be incorporated in the reduction process, which can be done either by 'infilling' or by Vajk's method. In practice the infilling is vastly simpler; in addition it seems more aesthetically appealing to make a single major assumption which is clearly understood to be incorrect rather than to be operating with a whole set of assumptions which may or may not approach reality. It must then be emphasised that the Bouguer Anomaly calculated in this way has no physical meaning, but is merely a computational convenience. The density chosen for the 'infill', although possibly making a considerable difference to the absolute values of the Bouguer Anomalies, has comparatively little effect on their gradients, the important quantity for terrain correction purposes. There therefore seems little reason for not using the standard upper crustal density of 2.67 gms/cc.

Apart from observations made on the surface of the sea, a very large number of the readings in Eastern Papua were taken along the coastlines, where the gravity field is also markedly affected by the form of the sea floor. Although these shape changes occur below the geoid, and so should strictly speaking not be considered in the Bouguer calculations, the factors mentioned above apply as far as interpretation is concerned. Because of this Map 3 (Extended Bouguer Anomalies), which includes the marine measurements, shows the land anomalies as calculated with 'infilled' seas. In addition to sources of error already discussed, therefore, Map 3 contains errors due to errors in bathymetry. For coastal stations these are probably negligible, but a probable error of one milligal is estimated in the case of marine anomalies. It must be remembered that, whereas for land stations the height of the topography above the geoid is of critical importance, the depth of the sea bed below the ship, which does not enter into the Free-air Anomaly for marine measurements, is not; a more significant

quantity is the average depth below the ship, a fact which has been taken into account in the computer program (Section 3.2).

As can be seen from Figure 3.4, the ship's tracks along which gravity readings were made intersect in a number of places. In general the agreement between values at these crosseovers is poor (i.e. worse than 20 milligals), but in most cases the error can be virtually eliminated by assuming a slight change in the cross-over position. Since at any rate for the Lamont and Hawaii data observed gravities should be accurate to better than 5 milligals, it is assumed that the cross-over errors are, in a large part, errors in navigation. The Shoup results are in some places quite unreasonable and could not always be contoured.

The navigation problem makes estimation of a probable error for the marine part of the survey an almost impossible task. In addition the contours drawn have had to be extrapolated across considerable distances of empty sea, and can in general be regarded only as a very rough guide to the overall form of the gravity field. Errors of over 40 milligals in a spot value deduced from the contour map in the marine area would not be surprising.

The geological correction is an extension of the marine correction described above, in that an attempt is made to allow for the effect of a sub-geoidal mass distribution. The geology of an area is seldom well enough known for such corrections to be made with any confidence and they are certainly not at present applicable in Eastern Papua.

3.2 The Terrain Correction Program

In recent years a considerable amount of interest has been shown in the application of high speed digital computers to the calculation of terrain corrections for gravity surveys. A number of papers

have been published on the subject, the methods described falling roughly into two categories according to the way in which the topographic data is digitised. Bott (1959) proposed a method in which the actual terrain is approximated by rectangular prisms of suitable cross-sectional area; this has been further developed by V. P. StJohn for surveys in New Guinea (StJohn and Green, 1967). An alternative approach, used by Takin and Talwani (1966), is to approximate topographic contours by straight sided polygons and input as data the coordinates of their vertices. The advantages of this method over the older (prism) approach are considered by its originators to be:-

(i) It takes into account the sphericity of the earth.

(ii) The data need to be prepared only once for any number of stations in the area.

(iii) The inner template zones of the conventional reduction techniques are also included in this method and need not be done separately by hand.

(iv) It is compatible with the conventional zones and can be easily joined with the outer zones whose topographic and compensation effects are given by the Isostatic Institute.

(v) The input data consist of topographic contours approximated by polygons.

(vi) The altitude of the station or depth of water below the station (when calculating the Bouguer anomalies at sea) can be directly used in the three dimensional computations.

(vii) The complete Bouguer correction (including the curvature correction) is computed in one stage instead of two, i.e. the simple Bouguer correction (for a curved slab), and the terrain correction.

In fact this list seems somewhat misleading. Not all the claims made are clearly advantages and some are apparently contradictory. For instance the compatibility with the conventional zones would be an advantage only if the corrections for some of these were in fact to be made by hand; the sphericity of the earth is also taken into account by StJohn in his development of Bott's prism method, and the last claim made, regarding the single rather than double stage computations, is only an advantage if it leads to a reduction in computer time used, which has not been convincingly demonstrated. Takin and Talwani claim a processor time of .3 minutes per station on an I.B.M. 7094 machine for the moderately rugged terrain of their example. In a typical regional survey involving over a thousand stations some five hours would be expended on this computer.

The major claims that can be made for the polygon approach are in reality only two and inter-related. They are that the time taken in data preparation is less and that the detail attainable in a typical digitisation is sufficient to obviate the necessity for further hand computations, even in the innermost zones. The extent to which these claims can be substantiated can best be seen by consideration of the zone charts used for manual corrections.

The Hammer Zones (Hammer, 1939) commonly used are so defined that in normal terrains there is no appreciable error introduced by averaging the height of each compartment, and also so that the contribution from each zone is often of the same order of magnitude. The radii of the zones (which are subdivided by radial lines into 6, 8, 12 or 16 compartments)

are 2, 16.6, 53.3, 170, 390, 895, 1530, 2614, 4469, 6653, 9903, 14741 and 21944 metres, and the corresponding areas of compartments within these zones are 213 m^2, 1343 m^2, 13645 m^2, 48382 m^2, 254865 m^2 (.255 km^2), .403 km^2, 1.176 km^2, 3.44 km^2, 4.77 km^2, 10.57 km^2, 19.26 km^2 and 51.89 km^2. Digitisation for computer calculations is normally extended beyond the outer Hammer Zone as far as the Hayford Zone O (outer radius 166.7 km); at any rate this must be done if easy joining with the outer zones computed by the Isostatic Institute (Kärki, et al., 1961) is to be an advantage. Obviously the degree of detail required in the topography varies enormously with distance from the station, and if the data is to be prepared once only for any number of stations in an area, then the maximum necessary detail must be digitised throughout. This would be an enormously lengthy process and its impossibility is in fact implied by Takin and Talwani later in their paper; short lengths of 'unclosed' contours are inserted in the immediate vicinity of the gravity stations.

It does however seem almost certain that, given an X-Y plot digitiser, the time taken to digitise contours, even in very rugged terrain, will be very much less than the time required to digitise the topography in terms of prisms small enough to give an equivalent accuracy in topographic correction. Without such a plotter the relative times taken in data preparation must be much more closely comparable. Admittedly it seems likely that far fewer polygon points than prism heights will be required to describe a given topography to the same order of accuracy, but each polygon vertex has to be specified by two accurately measured quantities. In addition, organisation of polygon data presents a much more difficult problem, important since typically in terrain correction programs much of the computer time is spent in data access. Polygon programs are, as was noted by StJohn (1967), also at a disadvantage because of their lack of facility for horizontally varying density and because of the relative

difficulty of extending them to the computation of isostatic effects.

Since StJohn's surveys were in New Guinea, terrain corrections were very important in his work and, as he points out, the corrections due to the outer zones are usually relatively larger for high altitude stations. However he seems to have taken preoccupation with far corrections to extremes. Calculations, on a rectangular grid, are extended for 5° around the station, i.e. out to a distance of about 540 km, yet, because of the coarseness of the digitisation, the effect of the terrain in the central block, of side about 55 km, which contains the station, cannot be calculated on the computer and has to be estimated by hand. In Eastern Papua, for most stations, the effect of this part of the topography was by far the greater part of the whole correction. A further drawback is that the topography is digitised on a rectangular grid, whereas hand corrections are made using a radial zone chart; the difficulty of estimating the effect of partial compartments inevitably increases the errors made. The problem is of less importance at the outer edges where it may be desirable to 'mate' the prism topography to a Hayford Zone, since in this case the prism sides are small relative to the zone curvature, but making corrections for topography beyond the O zone, as StJohn does, means that the published topographic-isostatic maps cannot be used.

The main advantages of prism methods are the flexible and easily ordered form of data storage and the great ease with which horizontally varying densities and isostatic corrections can be incorporated in the programs. In addition it seems possible that less computer time may be used, since the calculations involved, especially if the mass line approximation is used, are simpler.

The program described in this section, which is based on digitisation by prisms, was developed with the special needs of the BMR in mind. Gravity survey results, including barometric height reductions,

are routinely processed by the BMR on a CDC 3600 machine in Canberra, payment being made at roughly commercial rates. Under these circumstances the computation time is obviously important, and the limited core memory available necessitates quite stringent organisation of data storage and retrieval. Since repeated surveys may be carried out in the same general area, time spent in a more laborious digitisation may be well spent if resulting in a significant reduction in computer time on each calculation.

An additional constraint on the method to be adopted for Eastern Papua lies in the very poor quality of the topographic maps available. Routine digitisation of topography very close to the point of observation, where height differences of only a few tens of metres are significant, would introduce major errors where maps are not accurate to this level, and special methods were used for the innermost zones. Their treatment is described in Section 3.3; it is only necessary at this stage to note that their exclusion from consideration by the routine computer program eliminates one of the main advantages claimed for the polygon method.

On studying the available terrain correction programs it became apparent that, by sacrificing a certain amount of accuracy, a major increase in speed of computation could be achieved, using an approach which combined some of the features of the prism and the polygon methods; the topographic data is stored in prism form, but the actual calculations are based on annular zones. Prism heights are used merely to obtain suitable average height parameters for each zone, as described below.

As already been noted, the anomaly due to a cylindrical shell at an axial point is given by

$$dg = 2\pi\rho G \{(H^2 + R^2)^{\frac{1}{2}} + (h^2 + r^2)^{\frac{1}{2}} - (H^2 + r^2)^{\frac{1}{2}} - (h^2 + R^2)^{\frac{1}{2}}\}$$

A first requirement for expanding this expression is that the relative magnitudes of the quantities h, H, r and R should be known. If a cylinder is to be used to approximate to the actual topography, it is known that,in the outer three zones at least, the heights will inevitably be very much smaller than the radii, and it is necessary, in developing a generally applicable program, to ensure that this is always so. This is not possible if a total topographic correction is to be made in a single step, since in most surveys some stations will be at heights above sea level greater than the radii of some zones. It is much rarer for the average topographic level at a given distance from an observation point to differ from the height at that point by more than the distance of separation, i.e. consistent and sustained topographic slopes of more than 45^{o} are rare, and for at least some zones it seems that a two stage approach, relating the topography first to the level surface through the observation point, is likely to be simpler. In fact the computer time taken in the second stage, which involves computing the gravity effect of a solid cylinder and subtracting from it the terrain correction, is trivial.

A further consideration is that beyond a certain distance from the gravity station it is necessary to take into account the curvature of the earth. At such distances (in excess of about 30 km) the zone radii are always much larger than the mean topographic height, so that the entire program can conveniently be divided into two. In the first part an inner area is considered, a two stage approach is used and earth curvature is ignored; in the second the total topographic effect of an outer area is calculated in one step and allowance is made for the shape of the earth. The choice of the boundary between the two areas depends on a number of factors.

Consider first a Hammer-type zone with inner and outer radii r and R respectively. If it is possible to approximate the topography in this zone by a cylinder of height H relative to the station, the gravity equation becomes:-

$$dg = 2\pi\ G\rho\ \{(H^2 + R^2)^{\frac{1}{2}} + r - (H^2 + r^2)^{\frac{1}{2}} - R\}$$

which may be written:

$$dg = 2\pi\rho\ G\ \{R(1 + \frac{H^2}{R^2})^{\frac{1}{2}} + r - r\ (1 + \frac{H^2}{R^2})^{\frac{1}{2}} - R\}$$

which may be expanded by the binomial theorem, giving

$$dg = 2\pi\rho G\ \{R\ (\frac{H^2}{2R^2} - \frac{H^4}{8R^4} + \frac{H^6}{16R^6} \ldots) - r\ (\frac{H^2}{2r^2} - \frac{H^4}{8r^4} + \frac{H^6}{16r^6} \ldots)\}$$

$$dg = \pi\rho G\ \{(\frac{1}{R} - \frac{1}{r})\ H^2 - \tfrac{1}{4}(\frac{1}{R^3} - \frac{1}{r^3})\ H^4 + \tfrac{1}{8}(\frac{1}{R^5} - \frac{1}{r^5})\ H^6 \ldots\}$$

discarding terms in H higher than the sixth power. The effect of the higher power terms depends critically on the relative values of H and of r and R. As discussed below, the program for the inner area is based on the Hammer Zones down to Zone 1, for which r = 2.6 km and R = 4.4 km, and if H in this zone or in a part of this zone were to be 2 km, which is just conceivable, then the H^2 term would be .629, the H^4 term .181 and the H^6 term .061. Even in this extreme case, then, the sixth power term accounts for less than 15% of the total correction. This could, admittedly, amount to about a milligal but in such rugged terrain it is unlikely that the topographic data would be sufficiently good for very reliable calculations; in the rather more reasonable case of H = 1 km the contribution of the sixth power term is only about one part in five hundred. The land terrain program in fact ignores this, although a warning is printed out if H^2/r^2 for any ring exceeds a half. Obviously the fourth power term ought to be

taken into account, although this is not done in hand calculations, where the simple average height is estimated. Use of a straight average is the reason for the further segmentation of the Hammer Zones into compartments and in the computer program, in which the second and fourth powers of H are averaged, this is not necessary.

Choice of the range of operation of a terrain correction program based on the method outlined above is critically dependent on the size of the prisms used in digitisation. For Eastern Papua it was felt that the time available and the quality of the mapping precluded the use of prisms less than one minute square (for an area so near the equator such blocks are actually very close to being of square cross section, with sides of length one nautical mile, 1.852 km). With this decision made it was felt that the closest that the program could approach the station in processing the topography was 2.6 km; whilst there is no theoretical reason for zoning the topography according to Hammer's system, use of his zones allows easy checking of computed with manual calculations, and in this case the I Zone would, on an average, contain the centre points of twelve prisms and would also, on the apportionment system described below, be influenced by the heights of a further seven or eight. This is probably about the minimum necessary for the program to work successfully.

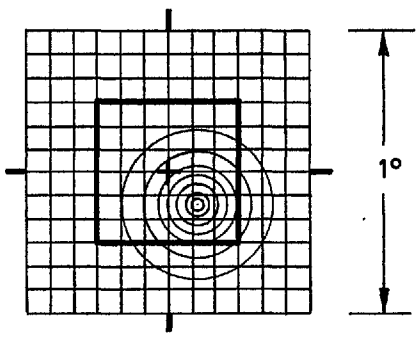
With this decided it seemed most convenient to digitise the topography in data blocks of 900, that is in squares of side thirty minute (55 kilometres), and process by the near-correction program all topography from 2.6 to 28 kilometres from the station. This is rather further than the Hammer Zones extend, but allows a particularly simple form of data organisation. A 'key point', intersection point of a whole or half degree meridian with a whole or half degree parallel of latitude, is first selected and the four half-degree blocks adjoining this point are called into store and ordered as a 60 x 60 array. All gravity stations

lying within fifteen minutes of latitude and fifteen minutes of longitude of the key point can then be processed.

The basic equation used for the inner zones (subroutine CYLNDR) is

$$dg = \pi\rho G \{(\frac{1}{R} - \frac{1}{r}) H^2 - \frac{1}{4} (\frac{1}{R^3} - \frac{1}{r^3}) H^4\}$$

The subprogram (flowchart Figure 3.6) operates on one station at a time and checks each 1' topographic block in turn for its position relative to the zone system, as shown in Figure 3.5



N.B. Each square on this diagram is of side 5', and contains 25 topographic blocks.

FIGURE 3.5

Values of H^2 and H^4, where H is the station height minus the prism height, are calculated and used to obtain the zone averages. Errors are introduced since some prisms intersect zone boundaries, and to reduce these the contribution of such prisms is apportioned between the zones concerned, four fifths to the outer zone, of which the prism forms part of the near station ring, and one fifth to the inner zone. With this rather primitive distribution system the program provides an approximation to the mean topographic effect not markedly worse than that obtained manually in the nearer zones and probably rather better in the outer zones, which contain several hundred prisms each (c.f. Table 3.2)

Apart from straight forward calculation of terrain corrections using a uniform density, facilities are incorporated in the program for varying the density of the prisms, for calculating isostatic anomalies and for making free air terrain corrections and marine areas corrections. Variable density is achieved quite simply by associating a density value with each topographic prism, and using these to derive an average density value for each zone. A special weighting function is used to obtain the average density of the cylinder to which the terrain correction from the zones is applied. For a prism height h and distance d from the station this function is $1 / d - 1 / (d^2 + h^2)^{\frac{1}{2}}$.

Isostatic anomalies are calculated on an Airy regional hypothesis, assuming that the whole of the central cylinder, radius 28 km, is compensated as a single unit. This might be considered a rather extreme version of the regional compensation assumption, although in StJohn's program the central prism, of side 55 km, is assumed to be compensated in this way. In view of the known departures of the real situation in Eastern Papua from any of the simple isostatic models, the effect is not likely to be important. As has been pointed out by Carey (1962), whether compensation occurs regionally or locally is to a large extent dependent on the time for which a given mass distribution has existed. Since the present structure of the Papuan peninsula is of comparatively recent origin any compensation is likely to be broadly regional.

Free-air terrain corrections are simply made by considering only those portions of prisms which extend above the station level, and using these in obtaining an average height parameter in a way similar to that used for Bouguer Anomaly corrections. Prisms whose upper surface lies at or below the station level are given a height value of zero in this averaging process. The masses above station level are also summed and the effect of their compensation at the crust-mantle interface

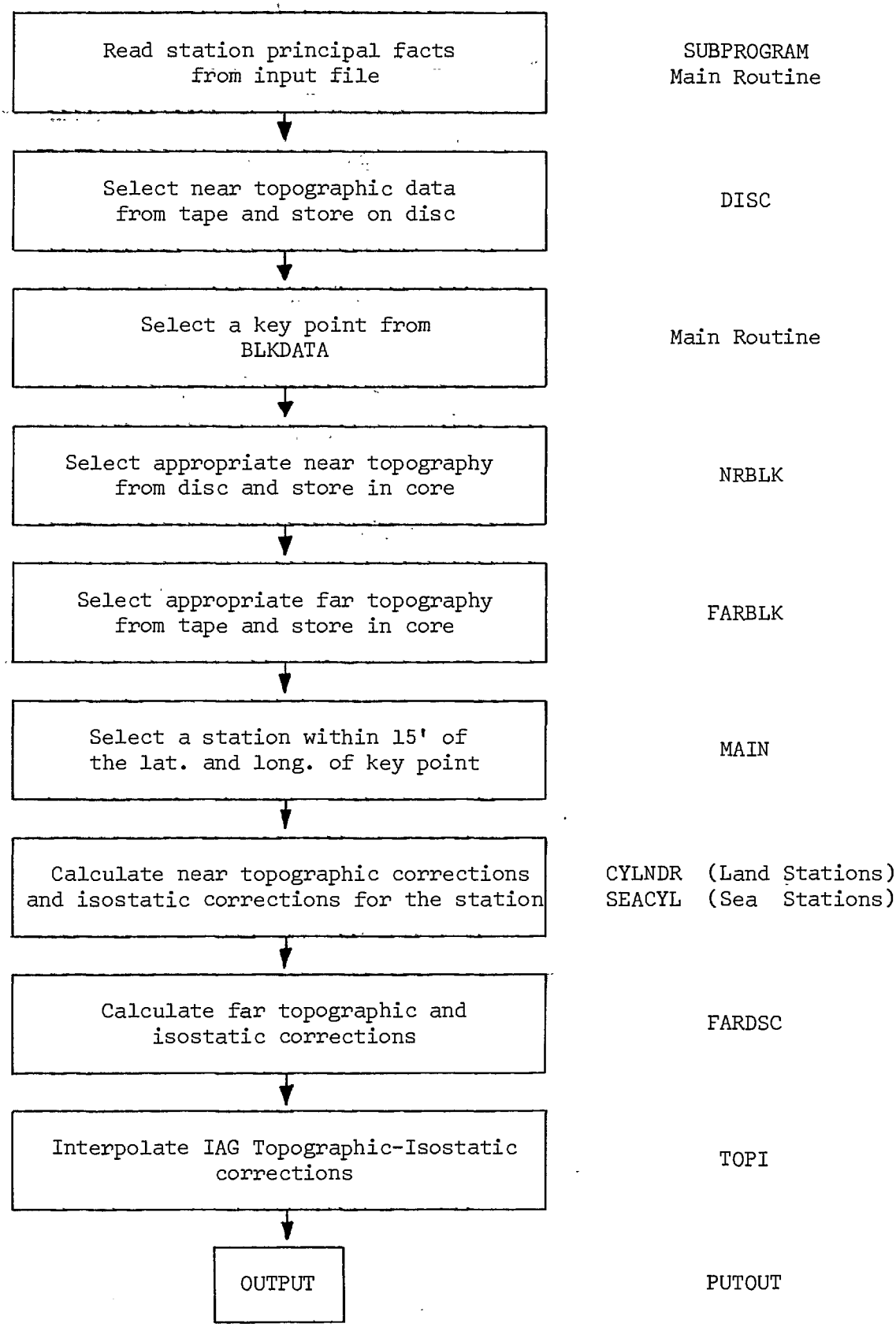


FIGURE 3.6 FLOWCHART, TERRAIN CORRECTION PROGRAM

is removed; reasons for this are discussed in the previous section.

Making terrain corrections for marine areas, by 'infilling' the sea with rock of a chosen density, presents some fairly major problems in terms of the present program, in which calculations are based on the effect of cylinders or annuli with one horizontal surface at station level. The method adopted is to calculate the effect of zonal annuli of the chosen density (standard density - sea water density of 1.03 gms/cc) using in the averaging process the station height for land prisms and the station height plus the prism depth for marine prisms. The effect of the annulus between the station and sea level is subtracted in the final stage of calculations. Because h, which is at least equal to the station height in this case, may be larger than r for the inner zones, this method is not applicable without validity checks, and special methods must be used where these checks fail. Since a check failure implies a high station it seems safe to assume that the contribution from marine areas in such a zone is very small and probably non-existent. This assumption is incorporated in the program, and, except where it is itself invalid, the marine correction so calculated is as accurate as the land terrain effects calculated by the same program.

The program as described above cannot be used for sea surface gravity measurements without considerable modifications, since in this case the topographic changes are occurring at some depth below the plane of observation, and in the inner zones the prime condition that r is greater than h may not be satisfied. This is similar to the problem encountered in making marine corrections to land stations, but is less easily circumvented. Zones in which r is less than or comparable to h can be excluded from routine consideration easily enough, but their further treatment remains difficult.

Since in the present thesis marine stations are used only incidentally and marine observations did not provide any sort of uniform coverage, the quick but rather inaccurate method of approximating the local bathymetry by a central cylinder bounded by horizontal surfaces was used. The height of this cylinder was obtained as a mean of the height of the included prisms, applying a weighting factor of $h/(h^2 + r^2)^{\frac{1}{2}}$. The bottom depth immediately below the ship at the reading point was assigned unit weight. This is a rough method of correction, but is certainly an improvement on the simple Bouguer plate. A separate subroutine, SEACYL, is used for marine stations.

Because of the pre-selection of Hammer Zone radii the results from subroutine CYLNDR can be directly compared with those from hand calculations using the Hammer Zone charts. Such a comparison was made using stations in the Kokoda region, possibly the most rugged in the entire survey area, and the results are given in Table 3.2.

A number of general features are immediately apparent. Firstly, in every case but one the machine computed terrain correction is greater than that computed manually, but this discrepancy is decreased if the apportionment described for prisms intersecting zone boundaries is used. Secondly the difference is generally only a small percentage of the absolute value of the terrain correction, and smaller than the inherent uncertainties in the correction due to poor topographic control. The discrepancies between hand and computer calculations are of the same order as those obtained by Takin and Talwani (1966) with their program and, as in their case, it is not really possible to decide which results are the more accurate. It seems safe to say that at any rate in Eastern Papua the major errors in terrain correction are due to the poor quality of the topographic data, and not to the simplifying assumptions made in CYLNDR.

Station	Zone M	Zone L	Zone K	Zone J	Zone I	Total	% Difference	
6615.0171	1.08	1.89	2.40	2.63	4.17	12.17		A
	1.35	2.11	2.21	2.87	3.94	12.48	2.5	B
	1.33	2.17	2.49	2.71	4.06	12.76	4.8	C
6615.0172	3.40	3.24	2.88	1.85	1.81	13.18		A
	3.71	3.78	2.83	1.64	1.63	13.59	3.1	B
	3.75	3.99	3.23	1.85	1.34	14.16	7.4	C
6615.0173	2.40	2.62	2.05	1.36	.97	9.40		A
	2.66	2.61	1.92	1.86	.73	9.78	4.0	B
	2.67	2.93	1.93	1.94	.63	10.10	7.4	C
6615.0174	.44	.76	1.08	1.02	.48	3.78		A
	.53	.73	1.41	.93	.59	4.19	10.8	B
	.54	.69	1.45	1.27	.41	4.36	15.3	C
6615.0175	2.53	2.45	1.91	2.47	3.01	12.37		A
	2.72	2.64	1.91	2.24	2.80	12.31	-.5	B
	2.56	2.73	2.10	2.39	3.14	12.92	4.4	C
6615.0176	.36	.56	.91	1.32	1.00	4.15		A
	.47	.66	.99	1.28	1.08	4.48	7.9	B
	.46	.69	.96	1.44	.96	4.51	8.7	C

TABLE 3.2

Comparison of manual Hammer zone calculations (A) with results from CYLNDR, with (B) and without (C) apportionment correction

r (km)	R (km)	r^{-1}	R^{-1}	r^{-3}	R^{-3}	C_2	C_4	C_4/C_2
4.5	6.6	.2222	.1515	.0110	.0035	.0707	.0075	.106
6.6	9.9	.1515	.1010	.0035	.0010	.0505	.0025	.049
9.9	14.7	.1010	.0680	.0010	.0003	.0030	.0007	.021
14.7	21.9	.0680	.0457	.0003	.0001	.0223	.0002	.009
21.9	27.7	.0457	.0361	.0001	.0005	.0096	.0001	.009

TABLE 3.3

Distance factors for gravity corrections

From 28 km to 166.7 km, the minimum distance for which topographic-isostatic corrections are published (Kärki et al., 1961), terrain corrections are calculated by subroutine FARDSC using a single stage process, since at this distance terms in H^4 may be safely neglected. This fact can be deduced from Table 3.3, in which C_2 and C_4 are the coefficients $r^{-1} - R^{-1}$ and $r^{-3} - R^{-3}$ of H^2 and H^4 respectively. If H = 2 km the ratio C_4 / C_2 is the actual ratio of these two terms; this is a rather extreme value, even for the outermost zone but could occur in the case of a station on top of an island volcano such as Manam (Territory of New Guinea). More usually H will be very much less than 2 km and the relative importance of the fourth power term will be correspondingly decreased.

Table 3.3 must be treated with some caution, since, because large height differences occur more commonly in the outer zones, it gives a false picture of the rate of decrease of terrain correction with distance. However it does indicate fairly conclusively that beyond the 27.7 km radius the effect of the fourth power term is likely to be negligible.

A further simplification introduced in FARDSC is the use of a non-varying density, since for the size of zones being considered density variations are likely to roughly cancel. The basic equation for FARDSC then becomes

$$dG = 2\pi\rho G \{(H^2 - h^2) (\frac{1}{R} - \frac{1}{r})\}$$

The field of operation of the subroutine FARDSC is divided, as for CYLNDR, into zones for which the factor $R^{-1} - r^{-1}$ is computed and the quantity $(H^2 - h^2)$ then averaged for all prisms whose centre point falls within the zone to obtain the height parameter. To reduce computing time the prisms in this case are of side 3'. Despite the larger size more than a hundred prism centre points fall within even the

innermost zone, and the use of apportionment for prisms straddling zone boundaries is unnecessary. Height parameters were averaged separately for prisms above and below sea level, so that marine corrections could be made or ignored, as required. FARDSC can be used equally for land and marine observations.

A factor which must be taken into account in computing terrain corrections for the FARDSC zones is the curvature of the earth. This can affect the calculation in a number of ways. Firstly the actual distance of any prism centre from the point of observation will be a chord distance and not the map distance, which is measured along the surface of the earth. Since the difference is small and since the distance is used only to allocate a prism to its appropriate zone this effect is not considered by FARDSC. Secondly the vertical through the prism will be inclined relative to the vertical through the station point, i.e. the zone element will be conical rather than cylindrical. Finally the zone element is lowered relative to the horizontal plane through the station point.

Figure 3.7 shows in diagrammatic form a section through the earth's surface in the vertical plane of the point of observation. Deviations of the zone shape from the cylindrical are related to the difference between s and c. The largest value for θ considered by FARDSC is $1\frac{1}{2}^{o}$ and since $s = R\theta$ and $c = 2R \sin \theta/2$ the difference in this case is less than one part in a thousand; its effect on the terrain correction will be even smaller. In the case of isostatic anomalies, which may involve zones with a vertical extent of more than 30 km, the difference

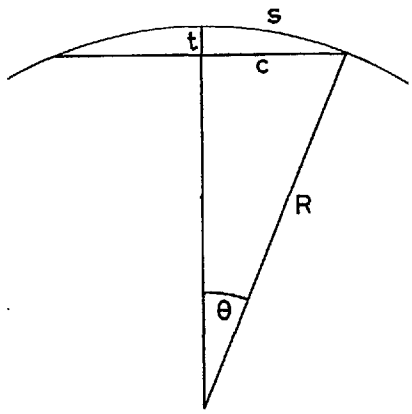


FIGURE 3.7

may not be quite neglibible, but will be sufficiently small, compared with the inherent uncertainties of isostatic reductions, to be ignored.

The relative lowering of the prism mass element cannot be ignored and must be taken into account in the calculations. In FARDSC, in common with the polygon program (Takin and Talwani, 1966), this is done by computing the relative depression of the mean line of each zone and assuming this can be used for the entire zone. The lowering (t in Figure 3.7) is given by

$$t = R\,(1 - \cos\theta)$$

For $\theta = 1\frac{1}{2}^{o}$ this amounts to 1.18 km, and an outer-most zone consistently at this height would give rise to a terrain effect of .3 milligals. The lowering is also applied to the isostatic compensating masses. Each zone was assumed to be divided into sixteen compartments for compensation, so that it was necessary to determine not only the simple distance of each prism from the point of observation, but also its bearing. Apart from this the FARDSC subroutine is simpler and less time-consuming than CYLNDR.

A number of program subsections within the main routine and minor subroutines complete the reduction package (flowchart, Figure 3.6). The 'program points', intersection points of whole and half degree meridians and parallels of latitude, are stored in the Block Data subprogram FACTS. Corrections for the distant topography and isostatic compensation for each program point read off the maps of Kärki et al., (1961) are stored in a data statement in subroutine TOPI, which determines by interpolation the effect at each station as accessed. The output, which includes the station principal facts and the Free-Air Anomaly, simple, terrain corrected and marine terrain corrected Bouguer Anomalies, Isostatic Anomalies, Topographic Isostatic Corrections and terrain corrections for very close topography (Section 3.3), is printed out and also punched out on cards in

coded format for further processing.

Routine processing of the data from the Eastern Papua surveys was carried out on the University of London CDC 6600; however in order to compare the time taken with that quoted by Takin and Talwani, a special run was made on the Imperial College IBM 7094 machine. Accurate comparison is not possible, since the time quoted for the polygon routine may include a proportion of the data access time. However if it is assumed that all the topographic data is already in core store (and with the example given this is certainly possible) it is fair to compare the 18 seconds claimed by Takin and Talwani as the computation time per station with the average of 4 seconds using the CYLNDR-FARDSC combination, once the near (IH) and far (IHH) blocks are in core. This is a very large saving, and is made more impressive by the fact that, in addition to calculating terrain corrections with both fixed and variable densities, isostatic corrections are also computed. As noted above it is difficult to compare the absolute accuracies because of the subjective element in manual corrections.

A listing of the terrain correction package, together with instructions for use, is obtainable from the Sub-department of Geophysics at Imperial College.

3.3 Local terrain Corrections

As described in Section 3.2, terrain corrections up to the Hammer Zone I (inner radius 2.6 km) were made using the average heights of 1' x 1' blocks. Because of the poor quality of the available mapping, more detailed digitisation, apart from being prohibitively time consuming, would probably have increased rather than decreased the overall error in Bouguer Anomaly; discrepancies of more than a hundred metres between the height of a point as obtained by barometric levelling and as estimated from the 1:250,000 maps are common, and the corresponding effect on the corrections calculated for the inner zones would be considerable.

Since the problem of making terrain corrections accurately in the inner zones appears insoluble, the magnitudes of the likely effects were investigated. For parts of the extreme eastern mainland and for the D'Entrecasteaux Islands, maps at a scale of one inch to the mile, contoured at intervals of 200 feet or less, do exist. In most cases the contours are classed as 'form lines' only and the general reliability of the maps, which date from the Second World War, is not high. Nevertheless, a reasonable picture of the terrain in the vicinity of a few gravity stations can be obtained. Twenty stations, in a variety of topographic situations, were selected, and the corrections for the Hammer Zones D to H (53 metres to 2615 metres) were calculated using a zone chart. The "map" height of each station was used in preference to the barometric height, as being consistent with the remainder of the topographic data. The 'topographic' and 'bathymetric' corrections were both calculated.

The corrections obtained, assuming in all cases a density of 2.67 gms/cc, are listed in Appendix B. There is a very wide variation, the greatest total correction being more than twenty milligals, for a coastal station near the highest part of Misima Island, with most of

the remaining values less than ten milligals. On the basis of these results subjective estimates were made for a further five stations. One of these five is in an area of eastern Misima contoured by B.M.R. geologists (De Keyser, 1961), and the remainder are in areas mapped at the one inch scale. This more detailed information was not examined until after the estimates, based on the author's own memory of the stations and the contours on the 1:250,000 maps, had been made. The corrections were then calculated using a zone chart. The difference between the two estimates was less than one milligal in all cases. These five stations are denoted by asterisks in the appendix, the estimated value being given in brackets after the calculated one.

Such a sample is admittedly far too small for a satisfactory estimate of the likely errors in the subjective method. However, in the absence of any alternatives, subjective estimates were made for the local corrections for all the remaining stations occupied. Where later contouring of Bouguer Anomaly showed that a certain value was of critical importance, a rough local contour map was constructed, based on the 1:250,000 maps, and the zone chart used. In no case did the subjective value differ from this "calculated" value by more than two milligals and it seems unlikely that the standard deviation of the gravity results is increased by more than one milligal by use of the subjective method. As would be expected, the errors increased with the size of the correction made, so that the uncertainty is greatest in mountainous areas. Unfortunately, errors in station height and position are also greatest in such areas.

All gravity stations were sited so as to minimise the corrections due to topographic masses within the zones A, B and C (i.e. out to 170 metres). Despite the generally rugged nature of the survey area, contributions from these zones were usually negligible; in the mountains

most of the river valleys are reasonably broad and flat bottomed, while coastal stations could usually be sited some distance from cliffs or the abrupt bathymetric slopes at the edges of coral reefs. The corrections from the innermost zones in a number of modelled cases of extreme local topography and bathymetry were calculated and used as guides in making subjective estimates, to be added where appropriate to the estimates for zones D to H. For example a correction of .9 milligals is appropriate to a typical steep sided valley with the gravity station twenty metres from the start of the slope.

In addition to the procedure outlined above, a second, less subjective, method was used. In this case the mean height of the topography in the innermost of the zones treated by the subprogram CYLNDR was determined, and a very near correction calculated within the subroutine on the assumption that the ring at the mean radius of this zone was uniformly at that height, and that the slope down to the gravity station was also uniform. This is analogous to the method used for the nearest areas by Takin and Talwani (1966). In the majority of cases the difference between the results of the two methods was less than one milligal, but where this value was exceeded there were often good grounds for preferring the subjective estimate.

3.4 The iterative 2-dimensional program

Quantitative interpretation of the gravity data in this thesis is based on the fitting to the observed anomalous gravity fields of the fields due to "two-dimensional bodies", i.e. bodies which may be assumed to be of constant cross section and density and to extend to infinity in the horizontal direction at right angles to the chosen profile. Talwani, Worzel and Landisman (1959) have shown that if the cross section of such a body is approximated by an n-sided polygon and if x_i and z_i (measured

positive downwards) are the coordinates of the i^{th} corner of the polygon, then the vertical component V of the gravitational attraction of the body at the origin of the co-ordinate system is given by

$$V_i = a_i \sin \Phi_i \cos \Phi_i \{\theta_i - \theta_{i+1} + \tan \Phi_i \log_e \frac{\cos \theta_i (\tan \theta_i - \tan \Phi_i)}{\cos \theta_{i+1} (\tan \theta_{i+1} - \tan \Phi_i)}\}$$

$$a_i = x_{i+1} + z_{i+1} (x_{i+1} - x_i) / (z_i - z_{i+1})$$

and

$$V = 2 G\rho \sum_{i=1}^{n} V_i$$

where Φ_i is the angle made by the i^{th} side with the positive direction of the x axis and θ_i the corresponding angle made by the line joining the i^{th} polygon corner to the origin.

A certain amount of care is necessary when preparing this expression for machine computations, since situations which involve dividing by zero or attempting to take the logarithm of zero must be avoided. In all such cases the expression given above for V_i can be greatly simplified. This is done in the FORTRAN subroutine PLYGON, developed in the course of this project, which calculates V at a single point for a single polygon. The arguments required to be supplied by the calling program are the coordinates of the point of calculation, the one dimension arrays containing the coordinates of the polygon corners in the same system and the number of sides and density or density contrast of the polygon. All these quantities are returned unchanged on completion of the sub-program. Other arguments are a parameter indicating the distance units in use in the calling program and the calculated attraction, which is

set to zero prior to each operation. θ and ϕ of the equation above are determined using the 'built-in' function ATAN2, which takes both x and z as arguments and ranges from π to $-\pi$, rather than the simpler ATAN which has a total range of two quadrants only. It was also found that the COS function was not sufficiently accurate in all cases and the value was instead determined exactly, using the known x and y values. In common with the other subprograms described in this section, a listing of the subroutine, which includes sufficient comment cards to explain the mode of operation, is available from the Geophysics Sub-department.

Subroutine PLYGON forms the core of a program designed to "fit" a geologically feasible two-dimensional model to the observed field; a flow diagram for the entire program is given in Figure 3.8. A feature of the approach is that no input file is read during execution, all the necessary information having been compiled into the program via a BLOCK DATA subprogram. Apart from giving a small saving in central processor time, this method has the practical advantage that a listing of all the input data is obtained automatically, without a large number of WRITE statements being used. In normal operation BLOCK DATA is the only part of the program to be compiled, the remainder being input in binary format.

As a first stage in establishing the data blocks, regions were selected within which the two-dimensional approximation was likely to apply reasonably well, and the anomaly field (Extended Bouguer Anomaly) was read off at a number of points along a line drawn across these areas at right angles to the strike of the gravity contours. Where possible and appropriate this line was drawn through or close to actual gravity stations, so that some of the subjective element inevitably present in contouring may have been eliminated. In general about a dozen readings were sufficient to define a normal profile.

The geological maps were then studied and model cross-sections containing one or more polygonal bodies with anomalous densities were formulated. The outcrop pattern represents a vital control on such models, and polygon corners determined from outcrop were held fixed throughout the subsequent operation of the program. Some, and in some cases all, the remaining corners were denoted as variable points and the x and z limits within which variation was permissible was defined. In this way iteration could be controlled so that later changes would not result in polygons intersecting. Also defined was the sense of the change in calculated anomaly which would be produced by movements of a polygon vertex in a given x or z direction.

With this data in core the fields due to the models, as originally specified, at the "gravity points" (points of known gravity) were determined by repeated applications of subroutine PLYGON, and compared with the observed anomalies.

Also compiled in the data block was a pre-determined value of the maximum allowable discrepancy between computed and observed fields. The actual discrepancies found were checked within the program and if it was found that one or more exceded this value, the largest of all was located and its sign determined. The coordinates of the three polygon vertices closest in the x-plane to this position were then passed to the subroutine VAR. Within this subprogram the polygon points were moved random distances in the directions of x and z which would tend to reduce the discrepancy; to ensure convergence of the program onto a single model the range of allowable variation was decreased each time a point was passed to VAR by closing off a fraction of the available range in the direction opposite to the motion. If it was found that the vertex in question was already effectively "against the stops" in the direction of motion it was removed from the list of variable points. The values of the model field

at the gravity points were then recomputed, using the modified polygons.

The program would go into its termination sequence for one of three possible reasons. Firstly if the maximum discrepancy had been reduced below that specified in the BLOCK DATA, secondly if the number of variable points had been reduced to zero; or finally if a specified operation time had been exceeded. In any of these three cases a call was made to one of the display subroutines DUMP or CADUMP. Both subroutines calculate the field due to the model at a number, typically about fifty, of equispaced points specified in the data block, and display the results graphically. In the case of the DUMP subroutine an approximate graph is drawn as part of the normal paper print-out, and the final polygon coordinates are also listed. CADUMP is a Calcomp or Kingmatic routine which uses the library program ARKIST to draw a smooth curve through the calculated gravity values, and also draws out the corresponding geological cross section, appropriately labelled. It is this subroutine, described in rather more detail in Section 3.5, which has been used to produce the illustrations in section 6.3.

The iterative program as described above proved moderately successful in that a large number of models were generated and tested without outside intervention. The internal criteria for comparing two models, i.e. that the "better" model was the one for which the maximum discrepancy between observed and calculated field was less, may not be the best possible; alternatives might specify a diminution in least square discrepancy or in the maximum deviation from a mean level of discrepancy (since the mean level can, to a first approximation, be altered merely by altering the level of the Moho). However in some cases either of these criteria would prove inferior to that actually adopted and in fact manual intervention every thirty or so models proved a simple and satisfactory method of arriving quickly at a good fit. The most time consuming part of

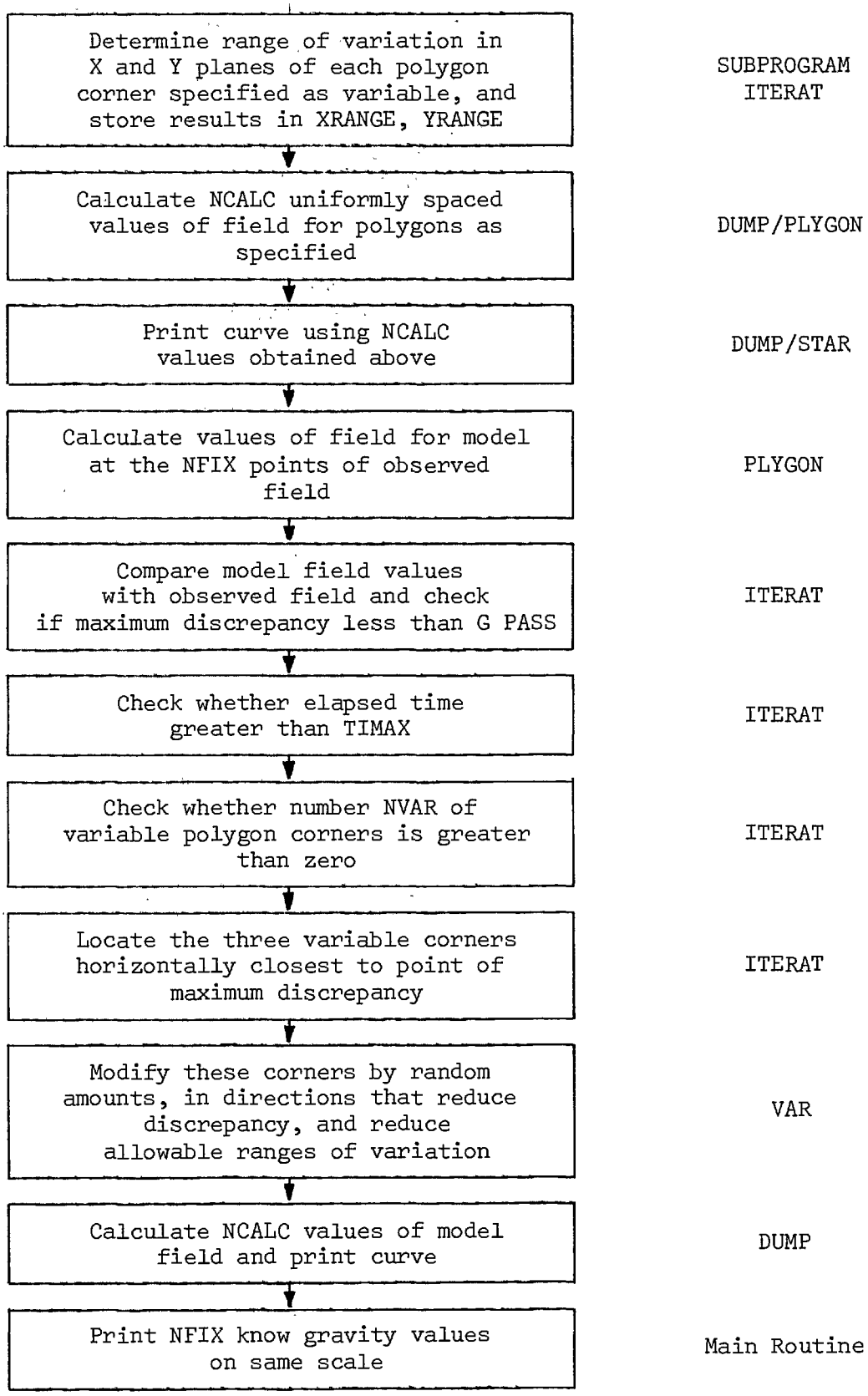


FIGURE 3.8 FLOWCHART, ITERATIVE 2-DIMENSIONAL MODEL PROGRAM

the entire operation was the initial formulation of the models.

Inevitably actual geological situations deviate from the truly two-dimensional, so that the models finally arrived at are not exactly appropriate even within the limits otherwise imposed by oversimplification on model studies. This point has been discussed in detail by Grant and West (1965) and by StJohn (1966), who come to rather different conclusions. In part this stems from their selection respectively of the ribbon and the mass-line as the basis of their calculations, but a more fundamental cause is the adoption by Grant and West of the criterion of 'agreement to within the limits of practical measurement'. Reference to the discussion on the measurement of gravity station heights (Section 3.1) shows that these limits, at least in the sense used by Grant and West, have scarcely been approached in Papua; a standard deviation of five milligals for Extended Bouguer Anomalies implies only a 95% accuracy even in the determination of anomalies of a hundred milligals, and, as StJohn (p. 77) shows, this degree of 'two-dimensionality' is attainable for the vast majority of New Guinea structures. A second point which might be made is that the models used are inevitably so oversimplified even in the plane over which variations are permitted, that the two-dimensional assumption, in places where the contours themselves show it to have considerable validity, does not seriously lessen the accuracy of the model studies. In Section 6.3 the limits imposed by this assumption are discussed only where errors outside the generous tolerances provided by defects in the original data are likely to occur.

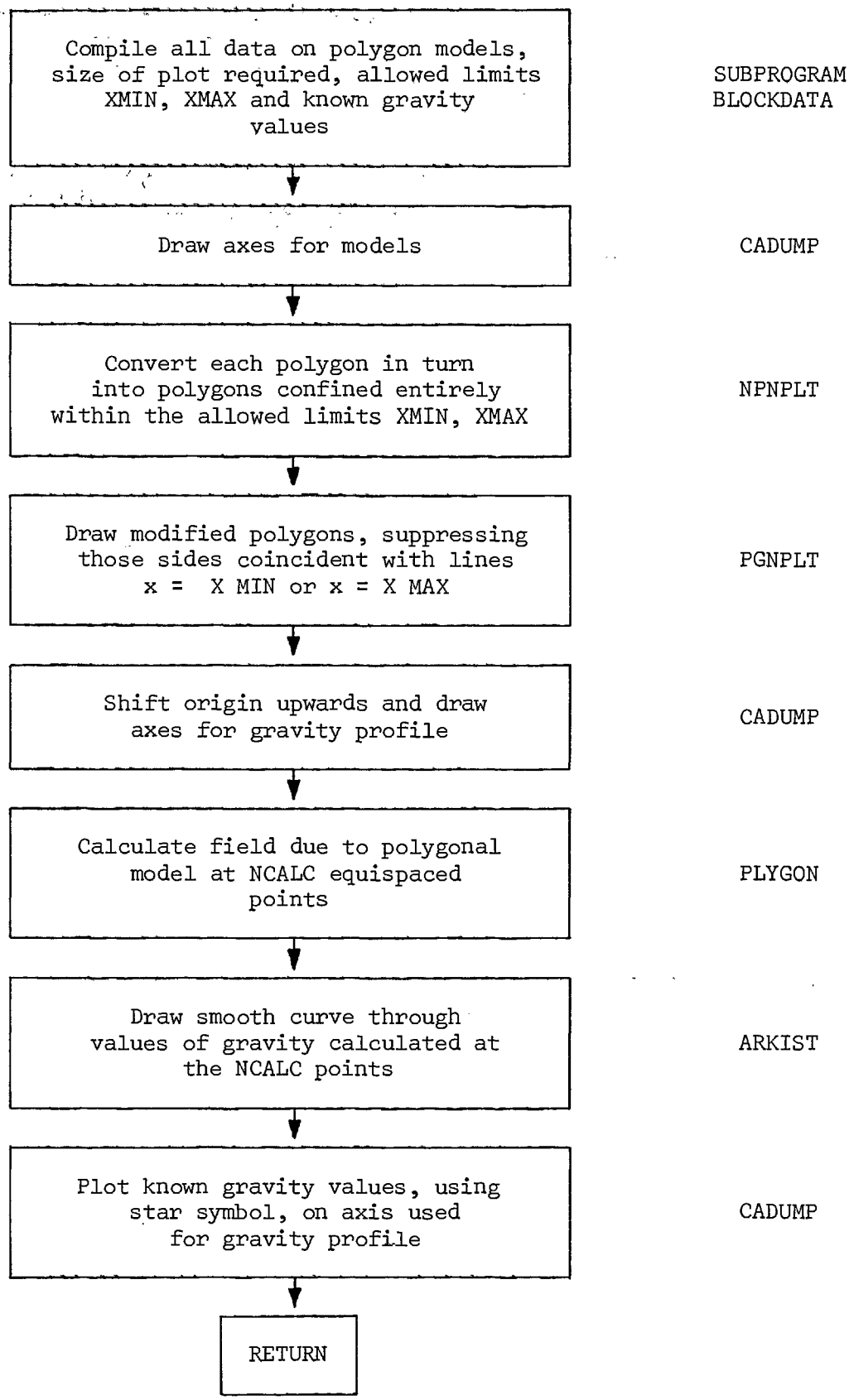


FIGURE 3.9 FLOWCHART, MODEL AND MODEL FIELD DISPLAY

3.5 Filtering and display programs

As noted in Section 3.2, the Free-air Anomalies (Map 1) have been smoothed prior to contouring, using the sinc function (Bracewell, 1965) as a weighting factor. This method was considered by St John (1967) but rejected in favour of use of the simple running mean (the Fourier transform of the sinc function) because of the reduction in computer time attainable. However, with the fast, large core store machines now available, time considerations are no longer of overriding importance and more weight can be given to the fact that aliasing errors introduced by the very uneven distribution of data points are exaggerated by the simpler approach. An additional refinement necessarily introduced along with the sinc function is use of the actual distances between the data points and the points of calculation, rather than the simple latitude and longitude differences. The smoothed Free-air Anomalies, being obtained on a regular grid, could be contoured by machine, using the program devised by P. Hubral of Imperial College for his own Ph.D. thesis (Hubral, 1970). Total running time, excluding contouring time, was of the order of two minutes for the whole of Eastern Papua.

The purpose of the subroutine package CADUMP (Flowchart, Figure 3.9) has been outlined in the previous section. Although basically very simple, a degree of complexity is introduced by the requirement that the sketch of the model cross section for which computations are made should be confirmed within reasonable limits. In all the models used in the present investigation some of the polygons would have extended far beyond such limits, and to avoid this happening in practice a two stage approach has been adopted. The BLOCK DATA subprogram (described in Section 3.4) contains, besides all the polygon data, arbitrary limits which are referred to in the drawing up of the CADUMP picture. The CADUMP package itself contains a subroutine NPNPLT which simply draws a polygon as specified,

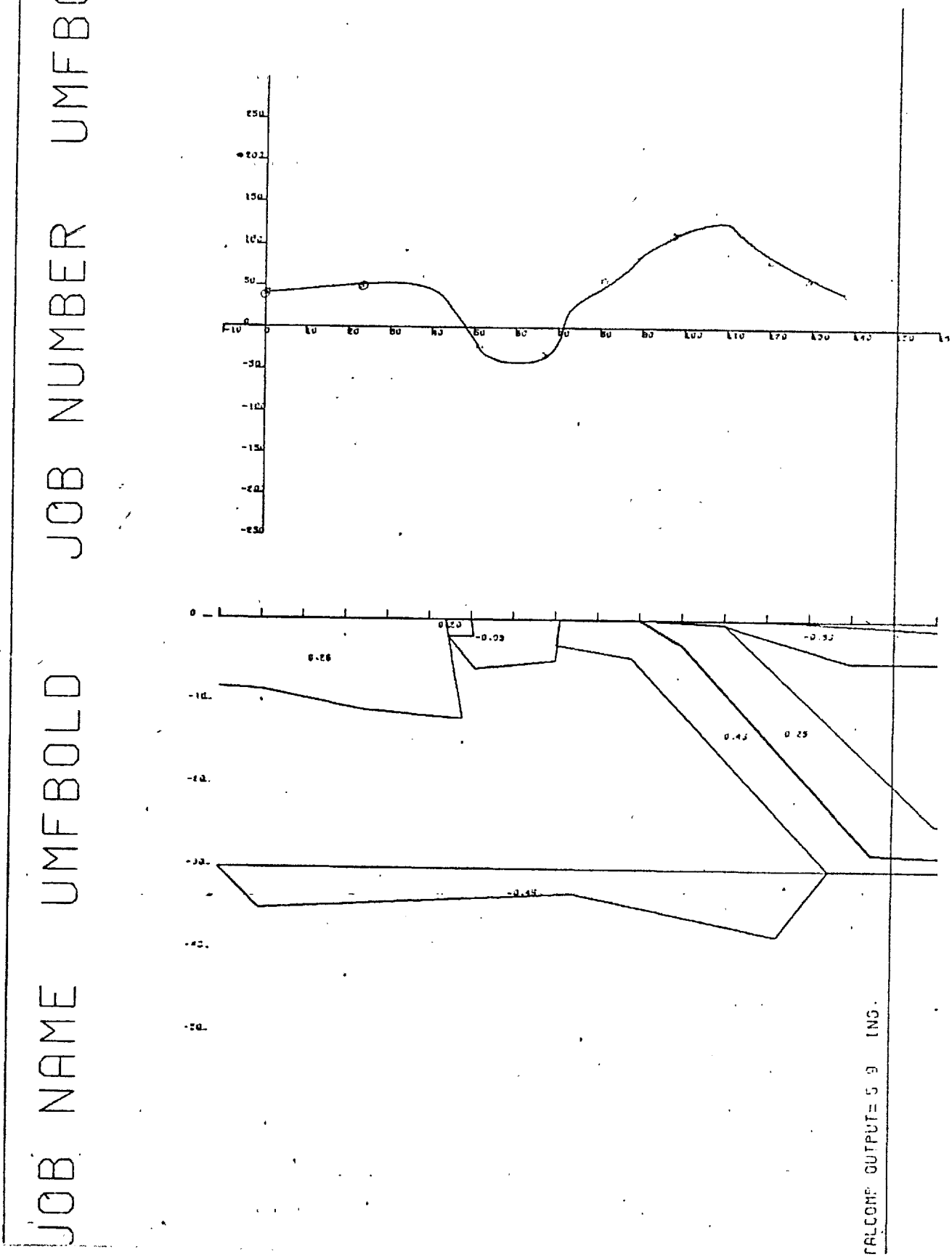


FIGURE 3.10 Typical CADUMP output.

checking only to see whether a side coincides with one of these limits; in such a case the pen traverses this section of the sketch in the "UP" position. NPNPLT is accessed only via the subroutine PGNPLT which transforms any polygon into one confined entirely within the limits specified and which is, within those limits, coincident with the original polygon. CADUMP calls PGNPLT as required to sketch the entire model, draws the smoothed curve through the model field via the library program ARKIST and plots the observed values of Extended Bouguer Anomaly on the same axes.

The models illustrated in Chapter 6 were originally produced as Calcomp outputs by CADUMP. Unfortunately, as shown in Figure 3.10, the output quality at the scale required is not sufficiently good for direct reproduction, and redrawing has been necessary. This stage should be eliminated by the forthcoming introduction of the Kingmatic flatbed plotter.

CHAPTER 4

GEOLOGY

4.1 The Evolution of Melanesia

Although systematic geological investigations in Melanesia date back to the closing years of the last century, and although very detailed work was done at a relatively early date in the gold mining areas of New Guinea, Fiji and the Solomons, the quantity of information generally available has increased dramatically in the last few years. In the main this represents the culmination of painstaking regional mapping programs undertaken by the geological surveys of the various territories, assisted in many cases by research workers from the universities of Australia and New Zealand. In addition, oceanographic expeditions, many of them using geophysical techniques as well as depth sounders and bottom sampling equipment, have recently obtained enormous amounts of data, filling out the structural picture deduced on the scattered island chains with information from the vast marine areas between them. Because of the complexity and diversity of its geology, Melanesia has historically been an area in which numerous conflicting theories of tectonic history and geological evolution have been formulated and tested; prominent in this field have been S. W. Carey, now Professor of Geology at the University of Tasmania, who developed his ideas of earth expansion and continental displacement (Carey, 1958) in the course of field mapping in New Guinea (Carey, 1938), and H. W. Menard of the Scripps Institution of Oceanography, who first postulated a "mid-oceanic" type Melanesian Rise to explain the observed dispersion of continental crust in the southwest Pacific (Menard, 1964) and who was instrumental in the mounting of the 'Nova' oceanographic expedition to study the area (Menard, 1969). Also prominent in the

presentation of tectonic hypotheses have been members of the New Zealand Department of Scientific and Industrial Research, and in particular of that department's Oceanographic Institute, an organisation which has generated within its own confines a wide range of conflicting tectonic theories (Summerhayes, 1967, 1969; Cullen 1967 a, b, 1970; Van der Linden, 1967, 1969, 1970). As a result of the recent acceleration in data accumulation and also of the recognition of the general applicability of the concepts of sea floor spreading and plate tectonics (but see Belloussov, 1970), an attempt can now be made to describe the structure and evolution of the area in general terms. The outline given here is probably incorrect in detail and may even be completely wrong, but at least forms a reasonable framework within which the more local problems of Eastern Papua may be examined and possibly resolved.

Of vital importance to the reconstruction of Melanesian geological history has been the discovery (Menard, 1969) that the great sea floor rises which characterise this area (Figure 4.1) are zones of crustal thickening and isostatic stability, and are not of the active, mid-ocean, type; of Menard's postulated Melanesian Rise only the Fiji Plateau, between the Fiji Islands and the New Hebrides, is still accepted as a current centre of sea floor spreading. The remaining rises are now commonly identified as rifted remnants of a geosynclinal complex formerly marginal to an Australo - Antarctic proto-continent.

The pre-drift reconstruction shown in Figure 4.2 is based on that of Smith and Hallam (1970). Cullen (1970) suggests that the separation of Australia and Antarctica was initiated by the Pacific-Antarctic Ridge and continued along the Indian-Antarctic Ridge; in attempting to accommodate to these two different spreading regimes (Sykes, 1970), the Australian segment has been further modified, peripheral layers being stripped off rather as skins can be peeled from an onion. The absence of

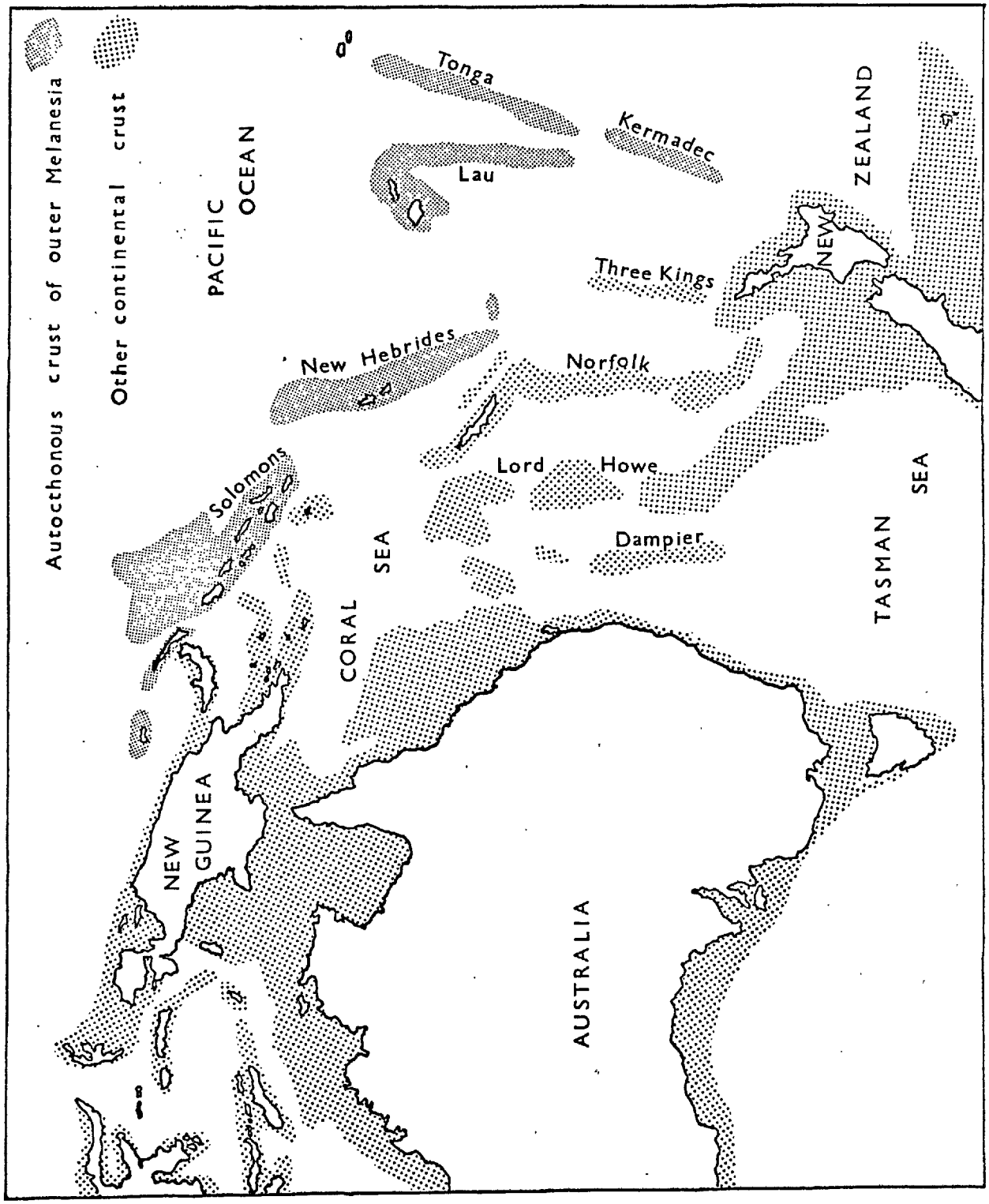


FIGURE 4.1 Melanesian submarine rises.

a major active rise in Melanesia may be attributable to the secondary nature of these later movements, and if this is so could be taken as an indication that such rises are the primary features of the world's tectonic pattern and not merely the inevitable accompaniment of any oceanic rifting.

Given such a pattern, it is immediately apparent that the two largest of the restricted ocean basins of Melanesia, the Tasman and Coral seas, have a common origin, and considerable similarity in the geologies of the land masses on their outer flanks (the so-called 'Inner Melanesian Arc' of New Guinea, New Caledonia and New Zealand) is to be expected. In the case of New Zealand and New Caledonia such resemblances have been commented on by Lillie and Brothers (1970); some of the resemblances between New Caledonia and the Papuan Peninsula are noted in the discussion of the gravity field of Eastern Papua (Chapter 6). Rocks of a geosynclinal sequence, presumably that which now also forms western Antarctica and the eastern seaboard and ranges of Australia, are exposed in all three.

Throughout the period of disruption of the Australian margin, new continental crust was being formed at the edge of the Pacific Plate by sea floor absorption, a process which has produced the autocthonous sequences of Fiji, the Solomons and the New Hebrides and today is building up thick crustal layers along the Tonga and Kermadec Arcs. Thus, although the two structures converge in New Zealand and probably, via the Bismarck Archipelago, in New Guinea, and although the same major tectonic movements have controlled their development, the 'Outer Melanesian Chain' is essentially independent of the inner islands and rises. The subsequent development of minor zones of extension in the Fiji Plateau (Chase, 1970) and the Woodlark Basin (Section 5.1) has further complicated the picture, leading in the first case to the impending collision between New Caledonia and the New Hebrides and in the second, possibly, to the somewhat anomalous

andesitic vulcanism of the Papuan Peninsula.

This vulcanism excepted, Eastern Papua is typically a part of Inner Melanesia, characterised by great masses of ultramafic rock in juxtaposition to geosynclinal sediments and metamorphics. The existence of these massifs, developed to their fullest extent on the Papuan Peninsula and New Caledonia, is one of the major problems presented by the area, and has provided the stimulus for the present study. It has recently been proposed (Mitchell and Bell, 1970) that the very much smaller and more localised outcrops of ultramafic rock in the outer arcs mark the sites of oceanic trenches, formerly (Milsom, 1970) on the Pacific side of the island chains. Such a solution seems less tenable in Eastern Papua, while the hypothesis of a simple mantle overthrust (outlined in Section 4.2 below) perhaps raises more questions than it answers. The problem is further discussed in the final chapter of this thesis.

4.2 The geology of Eastern Papua

In this section a brief summary only of the geology of Eastern Papua is presented. More detailed geological information is introduced as required in the interpretation of the gravity data (Chapter 6) and the discussion of the bathymetry of the Woodlark Basin (Chapter 5).

The regional geological map of Eastern Papua (Figure 4.3) has been prepared by H. L. Davies from published and unpublished data collected by B.M.R. geologists, and is included here with the permission of the Director, Bureau of Mineral Resources.

The central part of the island of New Guinea is a roughly trapezoidal block which forms the northern margin of the Australasian continent. The Papuan Peninsula extends from this block into the oceanic areas to the east and is the main emergent feature of a system of

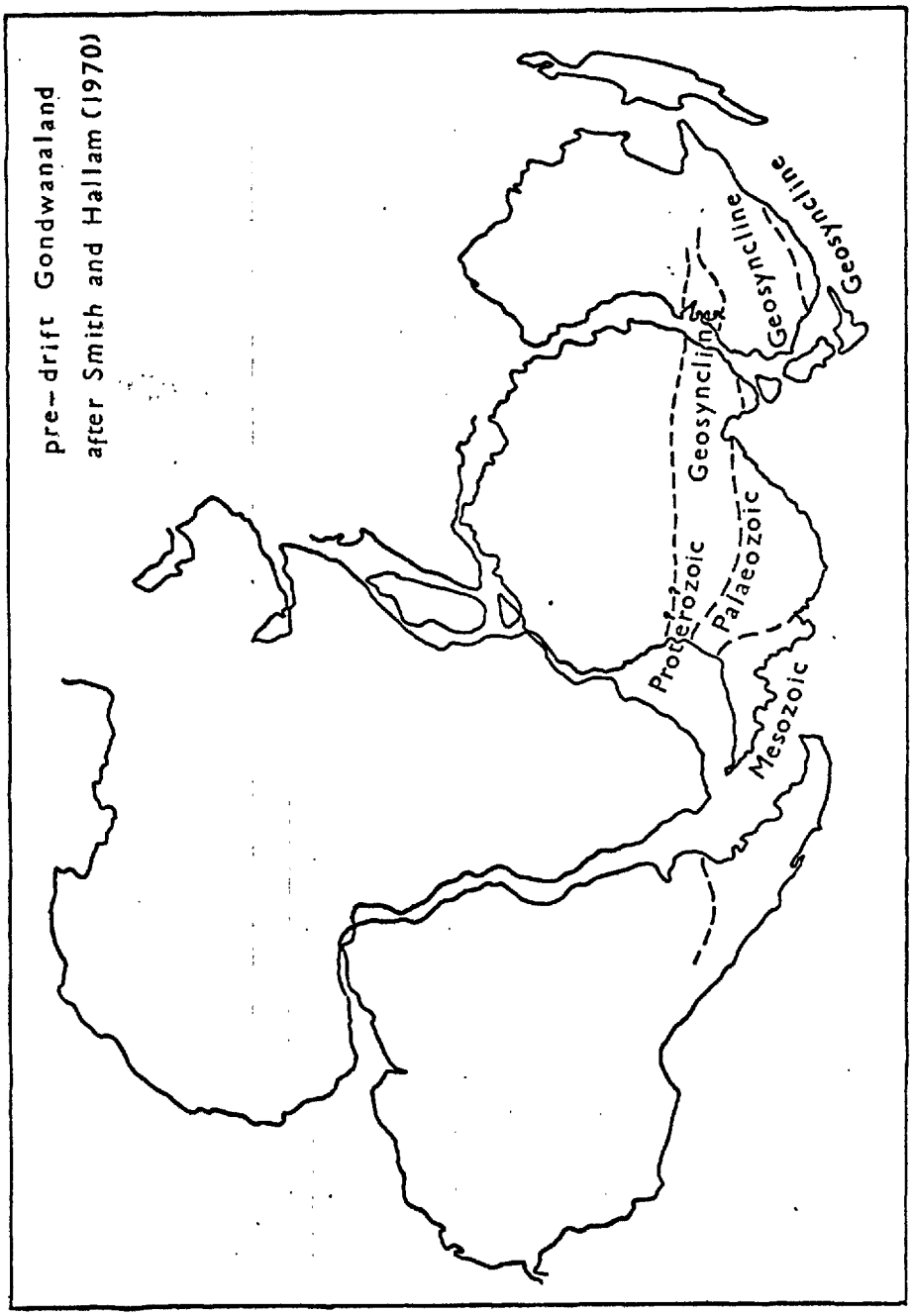


FIGURE 4.2 Possible reassembly of Australian marginal geosynclines.

structural highs which separates the Solomon Sea and Coral Sea basins. It consists of a south-easterly trending core of continental (sialic) rocks flanked by rocks of oceanic affinity. Sialic rocks occur about a line running slightly south of east from Goodenough Island through the offshore archipelagoes. Away from this line, islands have been built up of the products of mafic igneous activity and of coral limestone. Ultramafic rocks are widely distributed throughout Eastern Papua, most of the outcrop forming part of the Papuan Ultramafic Belt.

Sialic Rocks. Sialic metamorphic rocks are exposed in the Owen Stanley Range, the mountain 'spine' of the Papuan Peninsula, as far east as 148° 15'. These rocks, referred to collectively as the Owen Stanley Metamorphics, are not well known except near Wau, where they consist mainly of greywacke, phyllite and schist with minor amphibolite. Two metamorphic events have been noted by Smit (1969), each of which affected the whole of the exposed sequence. The only fossils described (Glaessner, 1949, Skwarko, 1967) are of Cretaceous age, but it is possible that some of the rocks present are older than this. The metamorphics are intruded by a biotite-rich granodiorite and by acid porphyries (Dow and Davies, 1965).

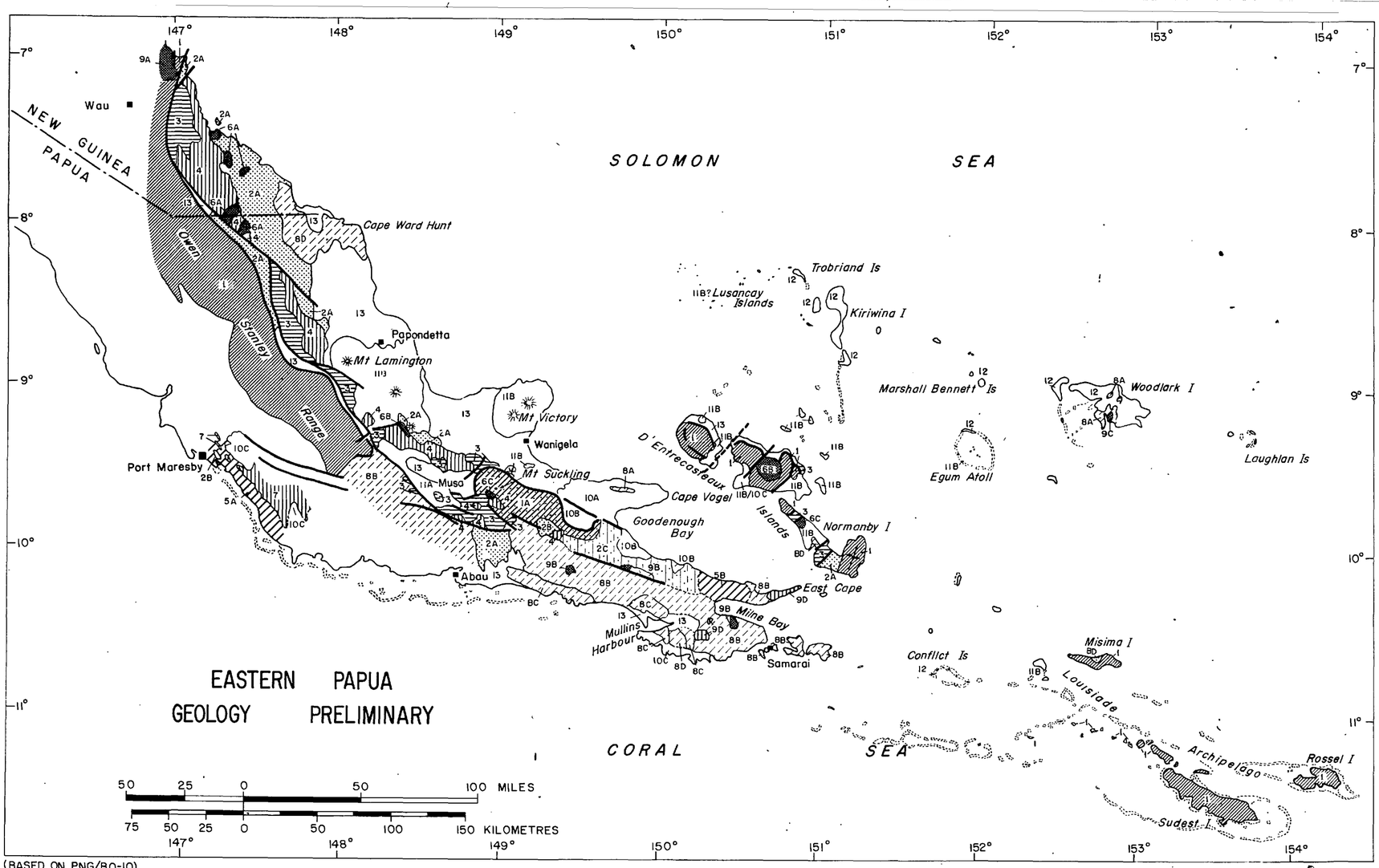
Except for two small granitic stocks and widespread quartz veining near Mt. Suckling (Davies, 1968a) and the andesitic volcanoes of Cape Nelson, sialic rocks are not found on the Papuan Peninsula east of 148° 15'. However, the D'Entrecasteaux Islands and Misima consist largely of sialic metamorphics and intrusives (Davies and Ives, 1965; De Keyser, 1961) and small granite outcrops and quartz veining have been reported from Sud-Est Island (Smith and Pieters, 1969). Davies and Ives (1965) suggest that the D'Entrecasteaux Islands at one time formed part of the sialic core of the peninsula and have been offset by transcurrent faulting. On Goodenough and Fergusson Islands the metamorphics are in the granulite or amphibolite facies, a significantly higher grade than in the Owen Stanley Range. They

form broad foliated domes about central plutons of granodiorite composition. On Normanby,(Davies, 1967), where metamorphic grade is lower, the intrusive rocks are granitic. Both low and high grade metamorphics are found on Misima, the latter being confined to the narrow eastern part of the island (Smith and Pieters, 1969).

Pliocene to recent andesitic vulcanism has built up the mountainous blocks of Mt. Lamington (Taylor, 1958), the Hydrographers' Range (Ruxton, 1966), Cape Nelson and isolated cones north of Mt. Suckling and in the D'Entrecasteaux Islands. None of these areas is very far from outcrop of older sialic rocks.

The Mafic Rocks. The remainder of Eastern Papua consists of mafic to ultramafic igneous rocks, coral and deep water limestones with minor chert, and Upper Miocene to Recent volcanogenic sediments. Two areas on the mainland, the Papuan Ultramafic Belt and the Suckling-Dayman mountain block, have special characteristics and, together with lithologically similar rocks from the D'Entrecasteaux Islands, are discussed separately below. Much of the remainder of the Papuan Peninsula consists of a monotonous series of marine basaltic lavas estimated (Davies et al., 1968) to be at least three kilometres thick. The sequence is intruded by gabbro north and south of Milne Bay and further west by syenite bodies. Very small dunite intrusions occur near the south coast of Milne Bay. Foraminifera in limestone beds intercalated in the lavas range in age from Upper Cretaceous to Mid-Miocene. Some of the Lower Miocene rocks were extruded in shallow water, but there are otherwise no obvious differences between lavas of different ages.

Oligocene lavas, some with well developed pillow textures, form the core of a faulted anticline on Cape Vogel. The occurrence of the rare mineral clinoenstatite in some of these lavas has



(BASED ON PNG/80-10)

PNG/82-12

LEGEND

QUATERNARY

RECENT	13	*Alluvium*	Superficial Suite
PLEISTOCENE & RECENT	12	*Raised coral*	
	11B	*Volcanics*	
PLEISTOCENE	11A	*Alluvium, folded*	

TERTIARY

PLIOCENE	10C	*Volcanics*	Superficial Suite
	10B	*Sediments, clastic*	
MID-MIOCENE TO PLIOCENE	10A	*Sediments, mostly clastic*	
LOWER MIOCENE	8D	*Sediments, volcanogenic*	
	8C	*Limestone*	
	8B	*Basalt lavas*	
UPPER OLIGOCENE	8A	*Basalt lavas, some with clino-enstatite*	
EOCENE	5B	*Basalt lavas and limestone*	
	5A	*Chert and calcilutite*	

MESOZOIC

CRETACEOUS	2C	*Basalt lavas some of which may be L.MIOCENE*
	2B	*Limestone*
	2A	*Basalt lavas and minor andesite, with some limestone*
	1A	*Metamorphics, basic and calcic, greenschist and blueschist facies*
CRETACEOUS ± OLDER	1	*Metamorphics, sialic, greenschist to amphibolite facies*

IGNEOUS INTRUSIVES

TERTIARY

LOWER OR MID MIOCENE	9D	*Gabbro*
	9C	*Quartz diorite*
	9B	*Syenite*
	9A	*Granodiorite*
OLIGOCENE ?	7	*Gabbro and dolerite*
EOCENE ?	6C	*Granite*
	6B	*Granodiorite*
EOCENE	6A	*Quartz diorite (P.U.B)*

MESOZOIC

CRETACEOUS ?	4	*Gabbro*	Papuan Ultramafic Belt
CRETACEOUS OR OLDER	3	*Ultramafics*	

Mt Lamington — *Active volcano*

Fault

Bouguer anomaly contour, milligals

been commented on (Dallwitz et al., 1966; Dallwitz, 1968).

Correlates of the basaltic rocks of the mainland extend east at least as far as Basilaki Island and probably to the marine hiatus east of the Engineer Group. Beyond this gap non-coralline rocks are exposed on Misima, Rossel, Sud-Est and in the Deboyne Group and the Calvados chain. Misima, as noted above, is almost entirely sialic. Rossel, Sud-Est and the Calvados Islands were formerly thought to be also sialic (Davies, 1958) and were tentatively correlated with the Owen Stanley metamorphics of the mainland, but recent work by Smith and Pieters (1969) has shown that quartz is absent throughout the archipelago with the exception of veining and a possible small granitic boss on Sud-Est. The western part of the Calvados Chain consists of basic volcanics and the remainder of the islands of basic volcanogenic sediments, and there is a small ultramafic intrusion on Rossel Island. The Deboyne Group is built up of basic volcanics of unknown, but probably Recent, age.

North of the D'Entrecasteaux Group a number of islands occur along the crest of the Woodlark Rise, a prominent east-west trending bathymetric feature. The majority are coralline, but basic volcanics intruded by biotite tonalite form the core of the largest, Woodlark Island. Cannac Rock, east of Woodlark, is probably built up of basic tuff similar to that found on the south coast of Woodlark (Trail, pers. comm.). Small islands in the centre of Egum Atoll are of olivine basalt, and some of the Lusancays are also volcanic.

The Papuan Ultramafic Belt

The sialic Owen Stanley Metamorphics are flanked on the north-east by an elongated discontinuous mass of mafic and ultramafic rocks. This feature, the Papuan Ultramafic Belt (Davies, 1968 a) extends some distance to the east of 148° 15', the limit of sialic outcrop, where it

becomes structurally more complex. Minor peridotite bodies on Goodenough and Fergusson Islands and major masses on Normanby Island are tentatively correlated with the belt on petrological grounds (Davies, 1967).

In the Bowutu Mountains (Dow and Davies, 1965) the belt appears to dip almost vertically, so that a complete cross-section is exposed. It consists of a basal mass of peridotite overlain by five to ten kilometres of gabbro, which is overlain in turn by a similar thickness of marine basaltic lavas. Diorite and tonalite intrude at the basalt-gabbro interface. The basalts have been dated as Middle Cretaceous and the tonalite as Eocene (R. W. Page, pers. comm.). Serpentinization is restricted to shear and contact zones and affects only about 20 percent of the exposed ultramafic rock.

Apart from their more mafic character the rocks of belt are distinguished from the other 'oceanic' rocks of Eastern Papua by their generally greater age and their structural position. A sinuous fault zone and valley of very valuable width separate the belt along most of its length from the rocks to the south and east. Highly sheared basalts and greywacke crop out in this zone. The valley is most pronounced in the west, where the fault zone seems to be almost vertical; further east the dips flatten and in the Musa region isolated ultramafic klippen are seen to overlie metamorphic rocks. Thompson (quoted in Dow and Davies, 1965) suggested that the ultramafic belt was a slice of oceanic crust and uppermost mantle which had been thrust south and west over Eastern Papua during the Eocene. Dow and Davies at that time favoured an intrusive origin, but Thompson's suggestion has since been adopted by Davies, who argues strongly for it in a recent paper (Davies, 1968 a). In later chapters this problem is reviewed in the light of the available geophysical evidence.

The Suckling-Dayman Mountain Block

At its eastern end the Papuan Ultramafic Belt overlies a series of basic and calcic schists. Similar rocks extend to the east for about seventy kilometres, forming a broad domal structure. Metamorphic grade decreases downwards, the lowest exposed member of the series being a moderately schistose metabasalt in which some pillow textures are preserved. The schists are thought to have formed the sole of the ultramafic overthrust and to have been metamorphosed during this movement (Davies et al., 1968). Upper Cretaceous foraminifera have been identified in some of the calcareous members. The domal structure and variation of metamorphic grade are most clearly developed in the central part of the block; at the western end the schists are overlain by serpentinised peridotite and intruded by granite, and in the east they are partly overlain by sediments.

Basic schists on Normanby Island resemble those of the Suckling-Dayman block and may also have been metamorphosed by an ultramafic overthrust (Davies, 1967).

Post Lower Miocene Sediments

Since the Lower Miocene the Papuan Peninsula has been subject to very rapid uplift and consequent rapid erosion. Coarse clastic sediments are characteristic of many coastal areas and provide a record of recent vertical movements. Sedimentary rocks are best exposed in the Cape Vogel-Goodenough Bay and Musa areas, where Plio-Pleistocene sediments have been uplifted many hundreds of metres. The Gwoira Beds of similar age, which occupy an embayment at the eastern end of the Suckling-Dayman mountain block, have been uplifted together with that block and tilted to the south, probably during slippage to the north, but dips in uplifted sediments are generally low. Normal faulting is common and seems to have formed the south coast of Goodenough Bay (Davies et al., 1968).

Evidence of Recent vertical uplift is also provided by coral benches on the mainland and most of the offshore islands. The most striking example is on Misima, where Recent coral is found at a height of more than 400 metres above sea level (De Keyser, 1961). The amount of uplift varies widely, even between closely adjacent areas, and the south coast of the Papuan Peninsula is currently a zone of subsidence.

CHAPTER 5

THE GEOPHYSICAL AND BATHYMETRIC BACKGROUND

5.1 Seismicity and generalised bathymetry*

Oceanographic investigations in northern Melanesia have mainly been concentrated in the Coral Sea and Solomon Sea oceanic basins, and the dangerous, reef-strewn waters between them have been largely neglected. However in 1968 the bathymetry of a major part of this area (Figure 5.1) was defined in detailed surveys by the Royal Australian Navy, along lines separated by distances of the order of two kilometres; the sounding charts (Royal Australian Navy, 1968) have been contoured by the author and used to update the map of the southwest Pacific prepared at the Scripps Institute of Oceanography (Menard et al., 1968). Compilation at this scale necessitates smoothing out of much of the fine detail shown on the original charts, but gives at least an idea of the complexity of the bottom topography and of the dominant structural trends. Sufficient data is now available from the area for some hypotheses to be advanced as to its structure and possible relationships with the remainder of the Melanesian complex.

*NOTE

The contents of this section have been accepted for separate publication in the "red" Journal of Geophysical Research, December, 1970.

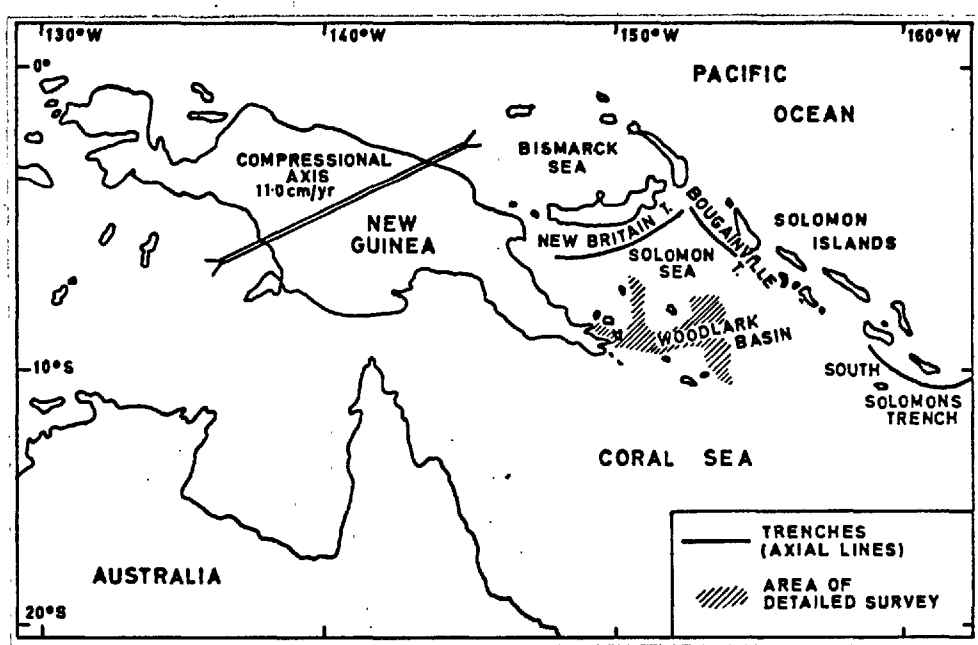


FIGURE 5.1 Northern Melanesia. Sea-floor spreading vector from LePichon (1968).

The first discussion in any detail of the sea floor between New Georgia, in the central Solomons, and the south-eastern tip of New Guinea, was given by Krause (1967). He named a number of the more prominent bathymetric features, including the Woodlark and Pocklington Rises and the Woodlark Basin which lies between them. Denham, in his description of the seismicity of the New Guinea-Solomon Islands region (Denham, 1969), noted a zone of shallow seismic activity extending roughly east-west across the same area, and correlated this with 'a ridge across the Solomon Sea' (presumably the Woodlark Rise). However Denham's illustrations show only earthquakes of magnitude 5 and over, and the pattern of seismicity is not clearly defined; more complete epicentre information for the period 1960-1968 is plotted in Figure 5.2. This data was extracted from the comprehensive epicentre catalogue maintained by the International Seismological Centre in Edinburgh; the most important primary sources were the United States Coasts and Geodetic Survey and the Centre itself. The very large number of shocks east and north of the general line of the Solomons Trench have been omitted for the sake of clarity, and it is immediately apparent that although some of the remaining earthquakes are related to the Woodlark Rise, there are a number of other active areas.

In the eastern New Guinea region epicentres are widely distributed throughout the Cape Vogel sedimentary basin and the northern and eastern parts of the peninsula, increasing in number towards the zone of intense activity associated with the New Britain Trench. Some activity is probably associated with continuing andesitic vulcanism, and with isostatic re-adjustments of the major ultramafic blocks, which are currently subsiding. In the western section of the Woodlark Basin epicentres also appear to be scattered almost at random, although most of them can be correlated with coral islands which have been subject to vertical tectonism. Unusually large focal depths, of the order of

150 - 250 km, have been computed for some of these shocks. Further east a narrower median active zone extends towards the island of New Georgia, its western limit marked by the deep meridional trough that crosses the main trend of the Woodlark Basin at 154° 15' E. Comparison with results from north-east Africa (Sykes and Landisman, 1964) shows that, while the level of activity may be similar to that in the Red Sea, the pattern observed in the eastern part of the basin strongly resembles that found in the more highly seismic Gulf of Aden.

Krause (1967) drew attention to the extremely rugged bottom topography of the Woodlark Basin and also to the predominance, at least in the western part which he investigated most fully, of east-west strikes; he considered (p. 42) that 'such a topography could only have formed through regional shear'. However both the trough at 154° 15' and the coral wall which forms the eastern bound of the Cape Vogel Basin run across this supposed shear for appreciable distances without major offsets, while in the east the dominant strike direction is rotated to the north-east. These observations are difficult to reconcile with the supposed importance of shear movements, and comparison with detailed bathymetric maps of parts of the crestal zone of the mid-Atlantic Ridge (c.f. Van Andel and Bowin, 1968) suggests the alternative hypothesis that the basin has been produced by dilational rifting normal to the dominant strike.

There are a number of other similarities between the Woodlark Basin and known submarine extensional rifts. Workers at the Hawaii Institute of Geophysics have recently reported abnormally low mantle velocities (Furumoto et al., 1970) and high heat flow (Khan and Woollard, 1969) from the same area. The eastern peninsula of New Guinea and the islands along the crests of the two bounding rises show evidence of strong differential vertical movements in the Quaternary, some of which appear to

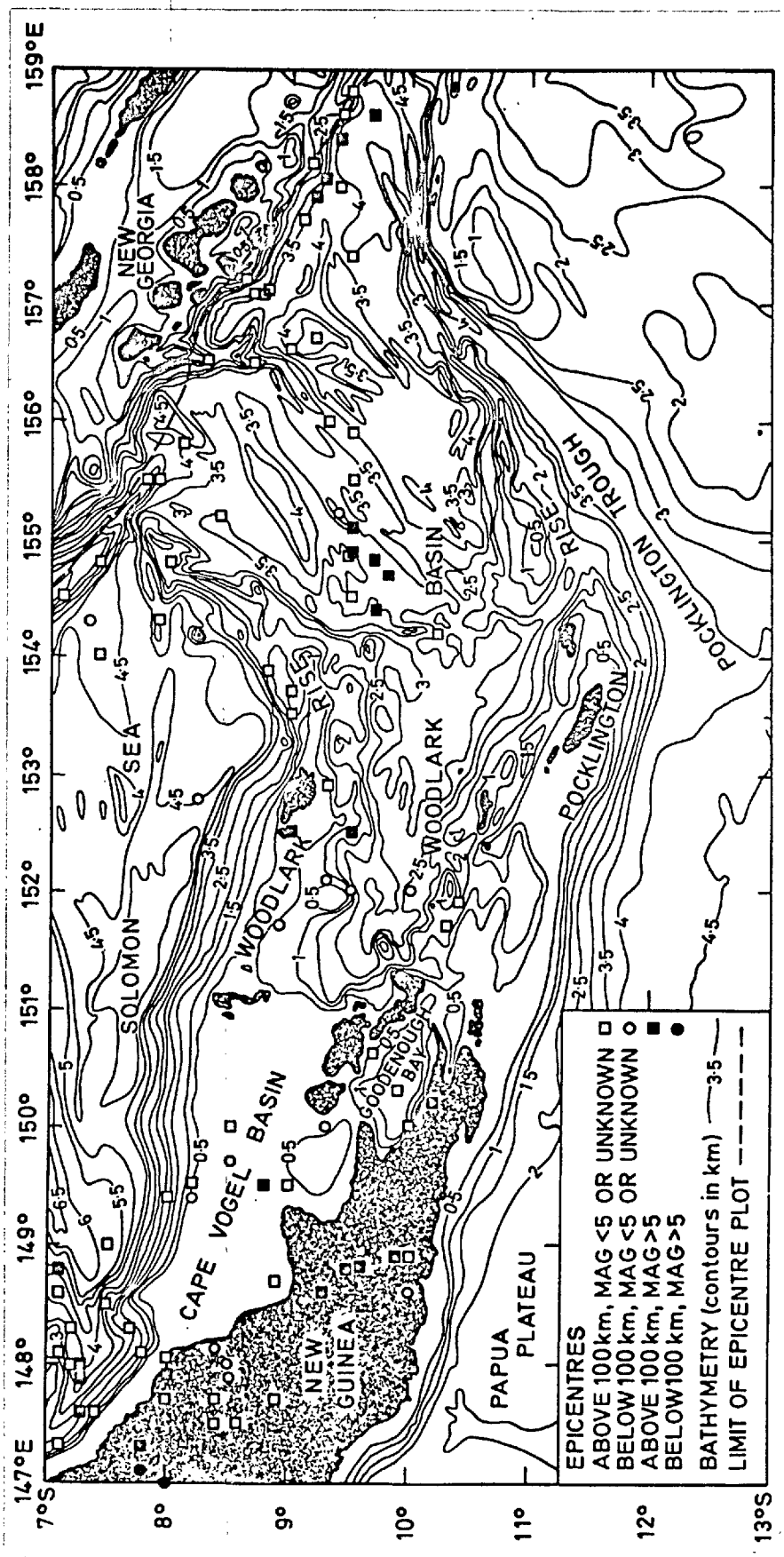


FIGURE 5.2 Eastern Papua; bathymetry and seismicity.

be related to present-day seismicity. The eastern part of the peninsula in particular is largely made up of ultramafic rocks and marine tholeiitic lavas, all of which are characterised by a very low potash content (Davies, 1969) and appear to be petrologically similar to rocks dredged from the mid-ocean rises (c.f. Melson et al., 1968).

The concept of the Woodlark Basin as an active centre of sea floor spreading is not new, although it has not had many supporters in the past. Carey (1958, p. 284) termed the basin the Louisiade Sphenochasm (from the Louisiade Islands on the Pocklington Rise), implying that it had opened about a hinge point near its western end. A fan-like movement of this nature would explain the absence of a clearly defined central rift. Carey's theory, which appears to be supported by the evidence now available, may also explain the seismic and bathymetric pattern around New Georgia. Denham (1969) emphasised the absence of a marginal trench in this area and the accompanying reduced seismicity; despite this the New Georgia Group is the main centre of vulcanism in the Solomons, containing over half the active or recently active volcanoes (Coleman, 1966).

Denham also suggested that the Australasian crustal plate spreading from the Indian-Antarctic Ridge is being absorbed at the New Britain, Bougainville and South Solomons Trenches; however the direction of relative motion of the Australasian and Pacific plates, as calculated by Le Pichon (1968), is almost parallel to the New Britain Trench (Figure 5.1). The existence of the trench as a prominent bathymetric and seismic feature is difficult to explain unless additional spreading centres are involved. As part of the interaction of the two major plates, the crust of the Woodlark Basin should also be turning down beneath New Georgia, but it is possible that the high angle rifting of the basin represents another form of response to north-easterly compressive forces. Even if some absorption is taking place, as the persistence of shallow earthquakes suggests, the

unusual thermal conditions associated with concurrent crustal formation could prevent the common pattern of a flanking trench and associated deep and intermediate seismicity from being developed. The main tectonic processes at present would appear to be normal faulting associated with tension and dyke injection in the Woodlark Basin and transform type shear of the newly formed crust past New Georgia. Stanton and Bell (1969, p. 114) have commented that 'far from being a monotonous accumulation of tuffs and andesites, the (New Georgia) islands contain some of the most basic lavas known, and a group of rocks showing affinities with both mid-ocean and island arc associations', a degree of complexity which accords well with the hypothesis presented here.

The exact location of active extensional regions in the Woodlark Basin is more problematical. It is tempting to see the trough at 154° 15' as marking a transform type fracture, although it is not markedly seismic. The association with the abrupt termination of the median seismic zone seems unlikely to be coincidental and it is possible that sea floor spreading is currently taking place at a slower rate west of this line. Some of the earthquakes along the Woodlark Rise may simply indicate areas of downfaulting of crustal blocks left unsupported by the opening of the rift; this would certainly seem to be the explanation of the epicentres around Goodenough Bay, the entire southern shore of which is defined by large normal faults. No explanation can be offered at the moment for the very deep shocks recorded in the western Woodlark Basin.

The association of central shoaling of a trench, enhanced vulcanism in the island arc and reduced deep focus seismicity appears to be repeated in the New Hebrides (Benoit, 1967; Warden, 1967), but in this group the active volcanoes are separated from the deep ocean by large non-volcanic islands on a frontal rise. Further investigation of the recurrence of this pattern in Melanesia may prove fruitful.

5.2 The Detailed Bathymetric Map

More detailed bathymetric contours of the western Woodlark Basin and the adjacent parts of the Woodlark and Pocklington Rises are shown in Map 5. The contours are based on the 1' x 1' block digitisation required for the terrain correction program, and in the sections covered by the Royal Australian Navy with very detailed surveys (Figure 5.1) themselves represent a certain degree of smoothing of the data available. However some other parts of the area, not included in this work, are almost devoid of soundings of any sort; a notable example is the deep sea floor north-east of Misima, shown as almost featureless but in all probability as disturbed as the rest of the basin.

At a first glance the impression made by the bathymetric map is that of an isosceles triangle with its apex pointing due west. The base of the triangle is formed by the deep meridional trough already discussed in the preceding section and which seems in detail a still more striking and remarkable feature. The remaining sea floor structures, many of which are intersected or truncated by the trough, strike roughly in the direction of the apex of the triangle, which lies about 30 km east of Normanby Island. A prominent seamount rises close to the surface near this point and the lineations of the basin are disrupted in several places by rather similar features, of which the most impressive is certainly Egum or Yanaba Atoll (152° E, 9° 20' S). Except for coral islets on the northern rim of the barrier reef and isolated volcanic fragments near its centre the atoll is entirely submerged and has evidently been gently tilted, south side downwards, in the recent past. The raised atolls of Gawa and Kwaiawata, due north of Yanaba, of the Trobriands and of the East Island group (centred roughly at 152° W, 10° 30' S) were also probably formed about volcanic cores; other wholly submerged but probably volcanic features are the seamounts at 154° E, 9° 40' S and at 154° 40 E, 10° 35' S and the

possible guyot just east of the Laughlan Islands at 154° E, 9° 10' S. The concentration of atolls, both normal and uplifted, along the 152nd meridian, coupled with the marked disruption of the crest of the Pocklington Rise about the same line are suggestive of a zone of weakness roughly paralleling the trough 200 km to the east. The western boundary of the basin proper at the Trobriands and the D'Entrecasteaux Group forms a third roughly meridional feature, markedly indented north and south of Sanaroa (151° E, 9° 30' S). This pattern of occasional prominent structural lines at right angles to the dominant strike direction is strongly reminiscent of the crestal zones of the mid-ocean ridges; it is noticeable that none of the three considered here can be traced beyond the limits of the basin.

On the inner flanks of the Woodlark Basin there are a number of high standing features which do not appear to be volcanic in origin; Misima Island, a mass of high and low grade metamorphic rock which rises steeply out of deep water to a height of over a thousand metres and on which coral benches occur at up to four hundred metres above sea level (De Keyser, 1961) is the most prominent of these. A number of other islands, Rossel (154° 15' E, 11° 20' S), Manuga Reefs (153° 25' E, 11° S), Renard (153° E, 10° 55' S) and the East Island group lie along strike from Misima, separated from the crest of the Pocklington Rise by relatively narrow zones of deep water. Of these Renard and Rossel are both built mainly of metamorphic rocks (Smith and Pieters, 1969) and the remainder are coralline. Krause (1966) postulated the major transcurrent 'Pocklington Fault' running west from the vicinity of Guadalcanal and ultimately continuous with the Owen Stanley Fault on the Papuan Peninsula, and from which he shows (p. 41) a number of smaller splay faults separating various crustal blocks on the Pocklington Rise. Whilst the evidence for the main fault as an extended feature is by no means conclusive, the bathymetry certainly suggests that fault zones spearate many of the islands, although,

in line with the hypothesis presented in the preceding section, the major movements are here seen as extensional rather than transcurrent. Misima itself is topographically strikingly similar to the Ruwenzori massif of the East African Rift, although on a much smaller scale; Carey (1958, p. 185) has hypothesised that this latter feature arose because "if the initial tension fractures (of a developing rift) should happen to anastomose, cutting off a block too small to command complete local isostatic compensation, this block would be bound to rise substantially higher than the main masses on either side of it because its own equilibrium would be swamped by its regional negative environment." The bathymetry of the northern slope of the Pocklington Rise certainly suggests that this process has occurred; in particular it is tempting to "replace" Rossel, together with its lagoon, in the apparently prepared position against the north-east side of the Sud-Est Lagoon. Interpretation of the structure of this area in terms of a number of anastomosing extension cracks directly related to the opening of the Woodlark Basin avoids the problem, posed if the faulting is transcurrent, and encountered by Krause (1966), of identifying the primary and secondary features. On the northern side of the basin the coralline Alcester Island, south-west of Woodlark, could be the top of a similar, though smaller, horst block or could be built on a volcanic fragment such as a section of caldera rim; the bathymetric information in the immediate vicinity of the island is not really sufficiently detailed to decide between these possibilities, but favours the former.

An abrupt change of strike of the Pocklington Rise and an offset of its crest occurs north-east of Rossel and is possibly associated with the intersection of the meridional trough, which lies due north of the island, with a fault along the north-east side of the lagoon. Some coupling between the Woodlark and Pocklington Rises in this area seems likely, since a rather similar pattern, including disruption by an

east-west trending deep, occurs on the Woodlark Rise.

The outer slope of the Pocklington Rise is comparatively smooth and featureless; this is true also of the Woodlark Rise except in the vicinity of the island itself, where a sharp offset in the contours suggests faulting, either normal with downthrow to the east or right-lateral transcurrent. The bathymetry is much more complex on the southern side of the island, but a similar fall in general level and a narrowing of the rise to the east can be detected, providing further evidence in favour of normal faulting. This point is referred to again in discussing the gravity data (Section 6.2); the proposed fault would roughly coincide with the volcanic rocks exposed in the central part of the island (Trail, 1967), which suggests some structural control of vulcanism. The present configuration of the coral platform which makes up most of the island indicates a slight Recent reversal of any such movement, coupled with gentle southward tilting of the entire block.

In addition to the evidence for extension seen in the main basin, Milne Bay and Goodenough Bay would both appear to be developing rifts, a contention supported by the very steep subsea slopes observed. Both features are very flat bottomed, presumably because of the blanketing of basement topography by Recent sediments; the rate of sedimentation into both, surrounded as they are by mountainous country, often of very soft rock, is extremely high, and in the case of Milne Bay has resulted in the development of an alluvial plain at the western end. The gravity results here (Section 6.1) suggest considerable relief on the bedrock surface.

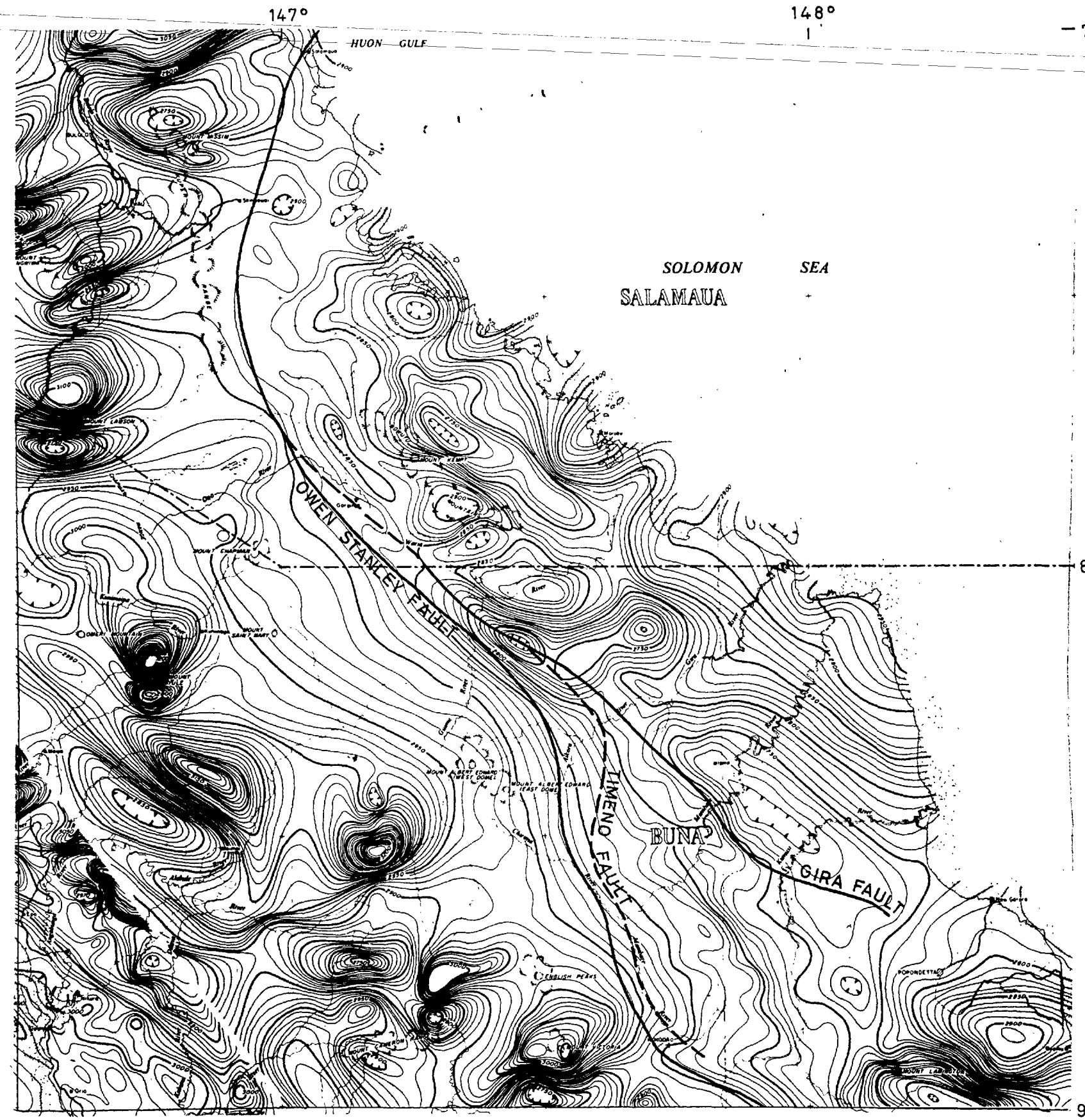
Examination of the detailed bathymetry of the western Woodlark Basin reveals additional grounds for favouring the extension hypothesis and no good reason for rejecting it. However one striking feature whose true significance is hard to assess is the lineation that forms the north side of the isosceles triangle, running from the north-east

first along the northern slope of the Woodlark Rise, crossing the rise along the south-east end of Woodlark Island, running between Egum and Alcester and thence via the East Normanby seamount to join with the thrust fault across Normanby proposed by Davies (1967). The alignment or apparent alignment of these features may be coincidental, but could be a major structural control.

5.3 The aeromagnetic survey

During the period June to November, 1969 an aeromagnetic survey of the Papuan Basin (Gulf of Papua) and of the northern part of the Papuan Ultramafic Belt was carried out for the Bureau of Mineral Resources by Compagnie Generale de Géophysique (C.G.G.). The section of the survey covering the belt was flown at a constant barometric altitude of 15,000 ft along east-west lines spaced at three mile intervals and along north-south lines at six to twelve mile intervals. Of the maps produced to illustrate the report (Compagnie Generale de Geophysique, 1969), the most generally useful are the total field contours and the structural interpretation, both at a scale of 1:500,000; elements from each of these have been combined, at reduced scale, in Figure 5.3. A regional field was evidently subtracted from the magnetic data prior to contouring, although this does not appear to be stated explicitly either on the contour maps or in the accompanying text.

The interpretative report provided by the company is rather brief and, unfortunately, is based on separate consideration of each of the 1:250,000 map rectangles, of side one degree of latitude and one and a half of longitude. This segmented approach has allowed the very large anomalies of the central Owen Stanley Ranges to be attributed to granodiorite batholiths near Wau and to basic volcanics and hypabyssal rocks further south, without any discussion of this supposed change in petrology



TOTAL MAGNETIC FIELD AT 15 000 ft A.S.L.
Contours and geological data from Bureau of Mineral Resources Record 1969/58

Fig. 5·3

or of the possible relationships between the different igneous suites. Also a prominent negative anomaly just south of the inter-territory border is correlated in one section of the report with a diorite intrusion and in another, at least in part, with the Gira Fault (see below); it is not otherwise suggested that the fault is a locus of intrusion.

In Figure 5.3 it can be seen that a zone of almost undisturbed magnetic gradient separates the anomalies of the central ranges from the very much smaller amplitude disturbances associated with the Papuan Ultramafic Belt. This lack of magnetic feature can be considered to be characteristic of the metamorphics of the Owen Stanley Ranges and of part of the Owen Stanley Fault Zone. C.G.G. note a linear low which is coincident with the zone near Garaina, but which strikes from there at 55° south of east towards Popondetta, roughly following the line of the Gira Fault; this latter (Davies, 1968a) is termed the Timeno Fault by C.G.G., a name more properly used to denote the eastern boundary of the Owen Stanley Fault Zone. They consider it to be the major structural feature of the area and that the ultramafics between the two faults are only a thin 'skin' overlying sialic rocks. An attempt has been made to support this interpretation by fitting the field observed along a line through Ioma (AA' on Figure 6.1) to the field calculated for a simple model. An overthrust dipping at about 5° between the Owen Stanley and Gira Faults is apparently suitable, although the degree of agreement between observed and model field is not stated.

A further point not commented on by C.G.G. is the apparent lack of correlation between geology and magnetic pattern in the extreme northern part of the belt, where peridotite outcrops in an almost magnetically featureless area east of the Owen Stanley Fault. This can be explained if the curved trace of the Owen Stanley Fault south-west of Salamaua was formerly continuous with the similarly curved trace west of Popondetta, and that subsequently about 80 km of left lateral displacement

has taken place along the Gira Fault; Dow and Davies (1965) have noted evidence for more than 4 km of very recent movement in this sense on the Owen Stanley Fault north of its junction with the Gira Fault. This would bring the magnetically quiet area between the Gira and Timeno Faults into close juxtaposition with the similar area south of Salamaua and, from C.G.G.'s interpretation of profile AA', would imply that the extreme northern part of the belt consists of a relatively thin tongue of material overthrust from the south-east.

The line AA' is almost coincident with the cross section IOMA selected for two dimensional gravity analysis (Section 6.3), in each case the deciding factor probably having been the width of the coastal plain, which there allows the main anomalies to be completely defined with measurements restricted to the land areas. Scattered depth estimates by C.G.G. suggest that at least 1000 metres of Tertiary and Quaternary sediments occupy a bedrock depression beneath this plain, a conclusion supported by the gravity data (Map 3).

CHAPTER 6

INTERPRETATION OF GRAVITY DATA

6.1 The anomaly maps: Papuan Peninsula and D'Entrecasteaux Islands

Treatment of the results of the Eastern Papua gravity surveys is here divided into three parts. In this first section the gravity field in the mainly emergent part of the survey area is discussed, in the second section discussion is extended to the predominantly marine areas and the third section is devoted to more quantitative consideration of a number of geological cross sections (Figure 6.1) and the corresponding gravity profiles. Four maps of gravity anomaly (Maps 1-4) have been prepared, the maps of Free Air Anomaly (Map 1), in which the smoothing process has tended to reduce field gradients, and of Extended (i.e. fully terrain corrected) Bouguer Anomaly (Map 3) having a contour interval of ten milligals. An interval of twenty milligals has been used for the maps of Simple Bouguer Anomaly (Map 2) and of Airy Isostatic Anomaly (Map 4), since in the preparation of each of these assumptions are made which, in some parts of the area, depart widely from reality. Contouring of the Simple Bouguer Anomaly has been extended rather further than on the other three maps, and includes data from a number of sea surface 'stations' for which detailed corrections have not been calculated.

All the anomaly maps are dominated by the region of high fields and steep gradients associated with the Papuan Ultramafic Belt. Detailed examination shows that the peaks of the positive anomalies are all offset seawards with respect to the main ultramafic outcrops, and that the magnitude of this offset increases steadily eastwards; in the Musa area, for example, partially serpentinised peridotites crop out in a region of comparatively low gravity field and the corresponding positive peak is centred in

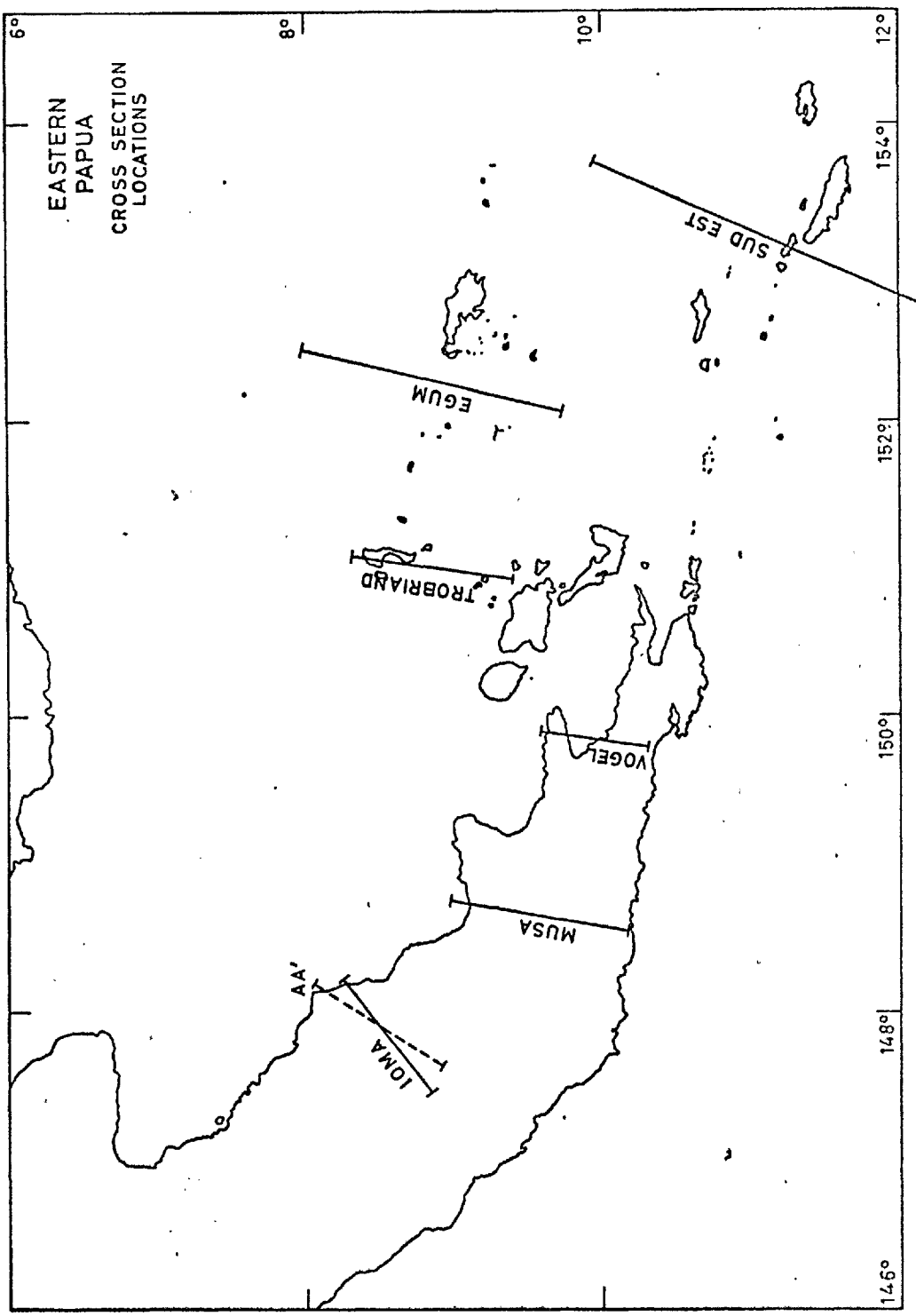


FIGURE 6.1 Location of cross-sections used in gravity models and (AA') cross-section interpreted by CGG aeromagnetic group.

the coastal swamps thirty kilometres to the north. The probable reasons for this pattern of offset, which has already been commented on by Davies (1968a), are discussed in more detail in the analyses of cross sections IOMA and MUSA (Section 6.2). Here it is sufficient to note that it is immediately suggestive of overthrusting of the ultramafic sheet from a root zone out to sea.

On the Isostatic Anomaly map the positive peaks are increased to still higher levels. This is an inevitable consequence of the outcropping of the high density source rocks in mountain ranges, since isostatic corrections become more positive as the mean topographic level rises. The system of correction used makes no allowance for the possible compensation of sub-geoidal mass excesses, and hence the question of the degree to which the ultramafic belt represents an undercompensated crustal load can be decided only on the basis of further analytical treatment.

Variations in gravity along the line of the belt are also of considerable importance, although less readily amenable to model studies. The ultramafic bodies outcrop as large podiform masses and the gravity pattern also suggests a "lumpy", although essentially continuous body. Peak anomaly values decrease eastward, an effect accentuated on the Extended Bouguer and Isostatic maps by the removal of the I.A.G. topographic-isostatic correction (Kärki et al., 1961), and the saddles separating the peaks become both broader and deeper. This evidence for a thinner and more fragmented ultramafic belt in the east central part of the peninsula is in agreement with the comparative paucity of ultramafic outcrop in the same area.

The majority of saddles and indentations in the belt anomaly are associated with Recent and continuing andesitic vulcanism. For example the major break at $147^{\circ}25'$E (south-east of Popondetta) coincides with the now dormant Hydrographers'Range volcanic complex (Ruxton, 1966), and the marked flexure in the main gradient a little to the west with the active cone

of Mt. Lamington (Taylor, 1958). The saddle roughly along the line of the lower Musa River, at 149°E, is also close to a major area of volcanic activity, although the existing vents, Mt. Victory and Mt. Trafalgar, lie rather to the east of the saddle axis. It seems unlikely that pressure within lower crustal magma chambers could cause fracturing of a formerly coherent sheet of ultramafic rock and more probably the breaks in the belt are primary features which have allowed the magma to rise.

The gravity pattern in the Musa region is strongly reminiscent of that reported by Crenn (1953) from New Caledonia (Figure 6.2). On this island large masses of ultramafic rocks, chiefly partly serpentinised peridotites, apparently overlie a Mesozoic geosynclinal sequence (Lillie and Brothers, 1970). Only minor positive peaks are associated with the ultramafic outcrops, but the value of Bouguer Anomaly increases as the north coast is approached and extremely high gradients are observed in the coastal region and just offshore. Crenn interprets this as pointing to the existence of a root or source zone for the ultramafics lying just to the north of the island. In Eastern Papua extensive coastal plains have been built up along the lower Musa by rapid erosion of Quaternary volcanics and the peak anomaly associated with what may be a very similar root zone can be defined by land measurements. The possible nature of such a root is further discussed in the final section of this chapter and in Chapter 7 (Conclusions).

A major problem is presented by the question of continuity of the Papuan Ultramafic Belt across Collingwood Bay. The bay is largely avoided by shipping because of the abundance of uncharted reefs, and since no marine gravity work has yet been attempted, the following possibilities must be considered.

(1) The belt may terminate abruptly and the scattered ultramafics of the D'Entrecasteaux Group may be related only causally, if at all, to the mainland outcrops. This solution would probably be unacceptable

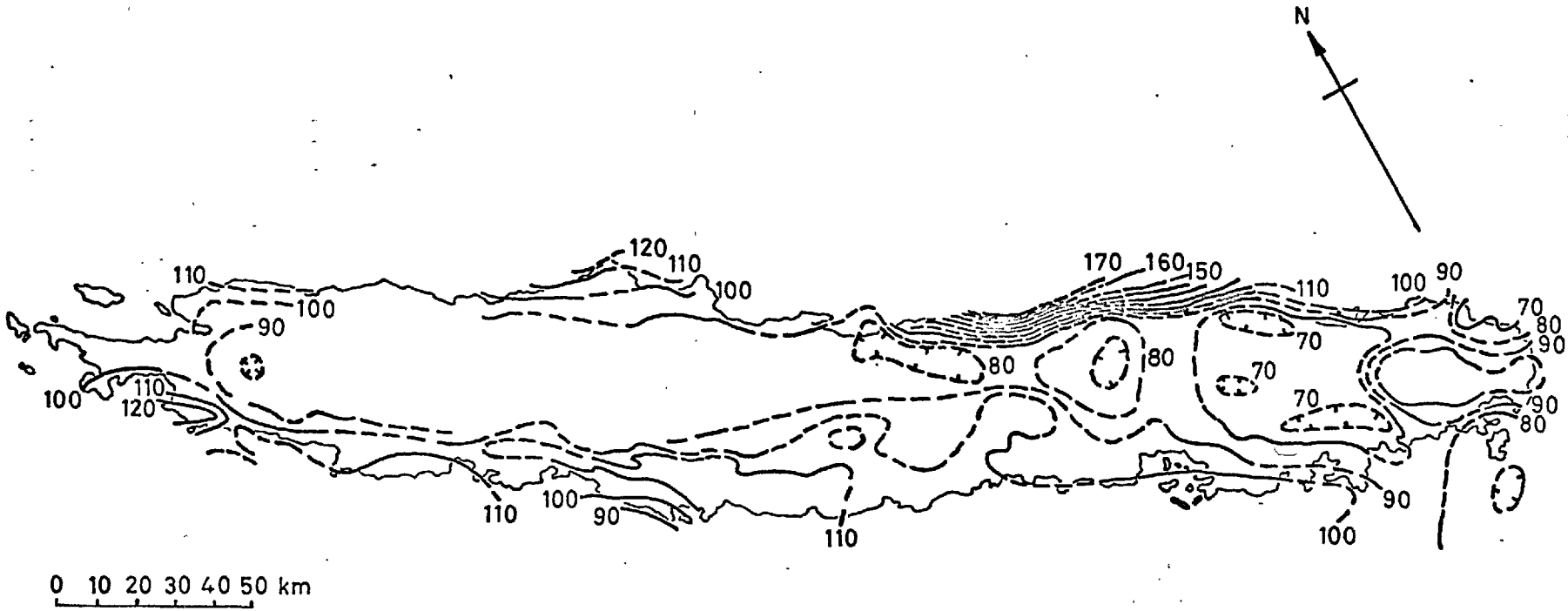


FIGURE 6.2 Bouguer anomaly map of New Caledonia
after Crenn (1953)

to advocates of the mantle overthrust hypothesis (Thompson, quoted in Dow and Davies, 1964), since it is difficult to see how a sheet of the type proposed can end other than gradually; it is worth noting that such a difficulty does exist in the case of the Troodos Massif in Cyprus, for which a similar proposal has been made (Gass & Masson Smith, 1963),and where no continuation of the linear gravity high can be detected beyond the limits of the island itself.

(2) The belt may continue across the bay in fragmented form, giving rise to the small but very sharp gravity high on Cape Vogel (see cross section VOGEL) and the ultramafic outcrops and associated small gravity anomalies on Normanby and Fergusson Islands (See below). This solution presupposes that the diminution of the gravity anomaly and increasing disruption of the belt observed on moving eastwards down the Papuan Peninsula are both accelerated in the offshore areas.

(3) A suggestion, originally put forward by Davies and Ives (1965) on purely geological grounds, but later given geophysical support by St John (1967), is that a major zone of transcurrent faulting exists in Collingwood Bay, offsetting all the structures of the Papuan Peninsula northwards. Since this solution involves consideration of the gravity field of the D'Entrecasteaux Islands, its treatment may be deferred until the remaining features of the western part of the peninsula has been discussed.

In the north western part of the survey area a minor but possibly economically important gravity trough tapers inland (southwards) from the coast near the mouths of the Gira and Mambare Rivers. On its western side the boundary of the low roughly coincides with exposures of the basic pillow lavas which form the uppermost unit of the Papuan Ultramafic Belt, while to the east the generally similar lavas of Cape Ward Hunt outcrop; these were correlated with the lavas of the belt (Patterson and Kicinski, 1956) but Davies (1968a) maps them as Miocene. Extensive swamps and alluvial

plains occupy the central part of the gravity anomaly, the only exposed consolidated rocks being a few mudstone bars of the Pliocene Mamama Formation in the bed of the Mambare River. The pattern shown on the gravity map, which in this area is based on onshore data only, may be somewhat misleading; the north-east trending gravity high which runs roughly along the line of the Kumusi River may be the truly anomalous feature, intersecting an otherwise comparatively regular monocline formed by the dipping upper surface of the Papuan Ultramafic Belt. Such a high presumably indicates the presence of a subsurface ridge of igneous rock which has developed since the belt moved into its present position. Coral limestones could well have enlarged any such ridge considerably before it was finally buried beneath sediment, and in fact minor limestone is seen in Robinson Bay, just south of Cape Ward Hunt, overlying the basalts. It is tempting to see in this feature the start of the Woodlark Rise, which appears to merge with the peninsula in this vicinity. The basin indicated by the gravity low, and in particular any coral reefs developed within it, could be a site of petroleum accumulation; it may contain up to 1500 metres of Upper Tertiary marine sediments in the onshore section,and appears to deepen offshore.

To the south of the Papuan Ultramafic Belt along the whole of its length runs a Bouguer Anomaly low associated with the sialic metamorphics of the Owen Stanley Ranges. This feature has not been fully defined by the present surveys, which in the western part of the peninsula covered only its north-eastern gravity gradient, but is known from previous reconnaissance (St John, 1967). It exists also on the Isostatic Anomaly maps, at least as a low relative to the very high values over the ultramafic rocks, but minimum anomalies are generally of the order of +20 milligals, in strong contrast to the -80 milligals of the Bouguer minimum south of Wau. In part at least the positive Isostatic Anomalies associated with the sialic mountains are due to the downward pull of the adjacent ultramafics, and

cannot in themselves be taken as evidence that the Owen Stanley's are currently above, or even at, their equilibrium level. This point is illustrated in the cross sectional analysis of the section IOMA. There is considerable geological evidence that the mountains are still rising, while the Papuan Ultramafic Belt is currently sinking not only with respect to the sialic rocks but also to sea level, as evidenced by the characteristic drowned coastline in the extreme north-west of the survey area.

East of 148°, at which point the metamorphic rocks cease to be of overall sialic composition, the axis of the low begins to track rather to the north of the main mountain ranges, passing beneath the Suckling-Dayman mountain block and then terminating abruptly at the western end of the Cape Vogel Peninsula. The coastal plain just west of this termination is remarkable for the absence of the large anomalies and steep gradients which abound in the remainder of the Papuan Peninsula.

The lowest Bouguer Anomaly values in the eastern part of the gravity trough, and Isostatic Anomaly values close to zero, coincide with Mt Suckling, south of Wanigela. West of the mountain, terraces of Pleistocene to Recent gravels have been elevated to heights of over a thousand feet above sea level, and evidence of Recent emergence is abundant; Goropu (Wai-owa) volcano, which erupted in 1943 and 1944 (Baker, 1946) lies close to the intersection of the gravitationally indicated line of weakness along the lower Musa with an east-west fault bounding the north side of the Suckling block, and activity was probably initiated by vertical movements on this fault. It seems certain that in this area at least isostatic equilibrium has not yet been reached, even though the majority of the exposed metamorphic rocks have probably been derived from basaltic extrusives and have densities similar to the unaltered basalts to the south and east. Quartz veining and a small granitic stock on Mt Suckling (H.L. Davies, pers. comm.) may indicate less basic, and lighter, rocks at depth.

Sialic rocks reappear in quantity in the D'Entrecasteaux Group and particularly on Goodenough and Fergusson Islands, where granodiorites were mapped by Davies and Ives (1964) as forming the cores of domes of metamorphic rocks. At that time the mafic character of the Owen Stanley mountains in the eastern part of the peninsula was not recognised, and these authors therefore postulated that the sialic 'core' of Eastern Papua had been offset northwards to the islands by transcurrent faulting. The offset idea was accepted by St John (1967), who saw further evidence in its favour in his Free Air Anomaly map; the more detailed work described here has to some extent nullified St John's arguments and, in the absence of geophysical information from Collingwood Bay,the problem must still be considered largely on the geological evidence. However a closer consideration of the gravity pattern in the Suckling and Musa regions, and in the D'Entrecasteaux Islands, is well worth while.

The form taken by the gravity trough near Mt.Suckling is in fact rather surprising. Although the mountain is undoubtedly the highest point in the area, it is relatively isolated, and the mass of rock above sea level over the axis of the low is quite small compared with that in the mountains occupying the region of uniformly high Bouguer and Isostatic Anomaly to the south. Even within the Suckling-Dayman massif the axes of the gravity low and of the mountain block are not coincident and the low ultimately runs out into the coastal plain. Obviously simple isostatic compensation of existing surface features does not adequately explain this pattern. In the discussion of cross section MUSA it is shown that a possible explanation is that the basic rocks along the line of the low are underlain by considerable thicknesses of sial, and that this is not the case further south. In the Musa Valley itself a deep, fault-bounded graben structure infilled with younger sediments could be the whole cause of the gravity anomaly; however since this is obviously not a satisfactory explanation for the deepest part of the low, at Mt. Suckling, the adoption of such a solution

for the Musa alone seems a needless complication.

If the gravity trough is in fact due to concealed sialic rocks similar to the Owen Stanley Metamorphics, then its abrupt termination at the western end of the Cape Vogel Peninsula requires explanation. In the analysis of cross section VOGEL it is shown that the high observed on the peninsula implies that large volumes of high density intrusive rock are present, extending from the surface to considerable depths. The simplest explanation for the presence of such rocks rather than sial in this position is that the latter have been displaced by transcurrent faulting, which would seem to be confirmed by the reappearance of sial in the D'Entrecasteaux Group. The low in the coastal plain west of the peninsula is open to the sea coast, so that the possibility exists that a line of negative anomaly links this area with the islands. Simple flexure of a supposed sialic belt would be a feasible means for connecting the outcrops but the gravity data favour faulting, at least in part.

South and east of Cape Vogel lies Goodenough Bay, a remarkably deep, steep sided and flat bottomed basin. The southern shore is formed by an impressive line of steep normal faults in Plio-Pleistocene marine and paralic sediments, and such faulting may also be important in defining the northern side of the basin. If the hypothesis presented in Chapter 5 is correct, and the geology of Eastern Papua is dominated by extensional tectonics, then the observed features in this area can be explained by assuming Collingwood Bay to be a locus of transform rather than transcurrent faulting. North-south or northeast-southwest (c.f. Davies and Ives, 1965, p. 53) extension east of such a fault could have resulted simultaneously in the lateral displacement of the sialic rocks now exposed in the D'Entrecasteaux Islands, the extrusion of the Cape Vogel lavas (Dallwitz, Green and Thompson, 1966) via a tensional crack in the crust and the subsidence of Goodenough Bay by normal faulting in a fashion analgous to that usually proposed for the origin of rift valleys (c.f. Freund, 1966). Still

further east such extension could also have resulted in the formation of the Milne Bay Graben. Coupled with this extension, uplift has occurred as evidenced by the extreme elevation of Recent deposits along the south shore of the bay; this seems to have been part of a general "overturning" of the Papuan Peninsula, the south coast and offshore reefs of which are currently sinking relative to sea level. Vertical uplift is, of course, a characteristic of the near-crestal zones of the mid-ocean ridges and it is quite likely that similar processes are at work in Eastern Papua. In this context it is worth noting a characteristic of the geomorphology of Melanesia which is particularly well developed in this area. The primary land form both of the Dayman-Suckling block and of Goodenough and Fergusson Islands is a broad, now partly eroded, domal structure, apparently the result of simple uplift of a central boss or belt by deep seated igneous intrusion. Davies and Ives (1965) suggest that the separate domes of the islands may once have been co-linear, enhancing the resemblance to the mainland massif. Linear structures of this nature might be expected in a rift zone, although petrologically the picture is complicated by the presence of andesitic and dacitic volcanics, unknown in the deep oceans, but possibly resulting from the quasi-continental nature of Eastern Papua.

The gravity pattern of the D'Entrecasteaux Islands themselves is relatively simple. As was anticipated, gravity minima were found to be associated with the cores of the islands, although not directly coincident with the granodiorite outcrops. The amplitudes of the Bouguer Anomaly lows are quite small compared with that of the mainland trough, but the persistance of the minima on the map of Isostatic Anomaly shows that they are unlikely to be entirely due to local crustal thickening in response to the topographic mass excesses. Certainly local isostatic compensation can play no part in the poorly defined elongated low paralleling the north-east coast of Normanby Island. This feature could be due to an offshore

sedimentary basin, but its close alignment with the lows on the other two islands suggests that the source may be a light acidic intrusion. At its northern end the Normanby low includes the acid-intermediate volcanic and solfataric region of Dobu and south-east Fergusson Island, which may be an indication of much larger volumes of intrusive rock of similar composition at depth; it has recently been suggested (Hamilton and Myers, 1967) that granitic batholiths develop in many cases under a cover consisting entirely of their own ejecta. If this is so, then structurally Normanby Island is much more similar to the other major islands of the group than at first sight appears. Ultramafic rocks on Goodenough and Fergusson Islands are confined to the fault traces which ring the central domes and in only one instance, in the north-east of Fergusson Island, are the gravity contours significantly affected. In view of the points discussed above, it now seems possible that the much larger ultramafic outcrops of Normanby Island are also marginal to a major sialic mass. The curving of the gravity highs around the supposed intrusion is consistent with such an interpretation, although geologically the complexity of the observed system of faults and the juxtaposition of contrasting rock types make any simple solution look rather implausible.

Insofar as it can be determined, the "background level" of Bouguer Anomaly in the D'Entrecasteaux Islands is considerably higher than on the mainland. This is a natural consequence of the thinning of the crust under the Solomon Sea, and, as is shown in the analysis of cross section TROBRIAND, does not necessarily imply a rise in Moho level immediately beneath the islands. Gravity anomalies north and east of the D'Entrecasteaux Group are largely associated with oceanic structures developed more fully further from the mainland, and are best discussed together with these. South of the islands the gravity pattern in the basaltic province of the south-eastern Papuan Peninsula, to which brief reference has already been

made, is of considerable interest.

The basaltic province, which includes the large offshore islands of Sideia, Sariba and Basilaki, is built up of a monotonous sequence of pillow lavas, ranging in age from late Mesozoic to late Tertiary, with scattered gabbroic and syenitic intrusions and minor intercalated limestones. With the exception of the syenites this sequence is characteristic of oceanic areas and it has been proposed (Thompson and Fisher, 1965) that oceanic crust is here exposed. St John (1967) pointed out that the position of the basalts relative to the sialic D'Entrecasteaux Islands made overthrusting of oceanic crust from the north unlikely, and that overthrusting from the south raised difficulties in resolving the geology of adjacent areas; he therefore rejected any solution that involved thrusting, noting that the observed elevation and gravity anomalies of the basalts could be explained either by assuming them to have been extruded over continental crust or to represent oceanic crust in situ overlying locally lower density mantle. More recently seismic refraction measurements in the Coral Sea (M. Ewing et al., 1970) have shown that the crust thickens to near normal continental values as the Papuan Peninsula is approached and confirm the improbability of any thrust movements from the south.

The presence of pillow lavas of widely varying ages, and the complete absence of pre-Quaternary terrigenous sediments does indicate a long history of submergence for this part of the peninsula, and raises the problem of the cause of its present elevation. For such a limited area the average level of Isostatic Anomaly of about +50 milligals does not necessarily imply isostatic disequilibrium; if lighter rocks underlie the basalts, and particularly if the mass is supported by low density mantle, the associated gravity low at the surface will be widely spread, leaving a residual positive Bouguer and Isostatic Anomaly over the actual outcrop.

This situation could have arisen in Eastern Papua. The

great thicknesses of sialic metamorphic rocks exposed in the Owen Stanley Ranges between Wau and Woitape (Figure 4.3) show that at least as late as Upper Cretaceous times a deep linear basin existed in this area and in all probability extended to and beyond the present-day end of the Papuan Peninsula. Sediment fill in this basin was probably almost entirely in the form of turbidites derived from the 'anchoring' continental block, a situation analogous to that now existing in the Aleutian Trench. The majority of narrow elongated sea-floor depressions, whether extensional or compressive features, are associated with extrusive activity and, as has been observed in a number of cases (c.f. Menard, 1964, p. 114) lava dams may be formed, ponding back sediments. The creation of such a dam west of the present day basaltic province prior to the Upper Cretaceous would account for the lack of clastic sediment,since the only fill available from that time onward would have been pillow lava and pelagic detritus, now exposed by the emergence of the Papuan Peninsula. On the extension hypothesis this uplift is seen as the result of expansion and partial melting in the upper mantle. The evolution of the peninsula is further discussed in the final chapter.

Gravity values rise steeply from the central gravity low of the peninsula along the northern boundary of the basaltic province. In this, western, end the arguments summarised above against overthrusting do not entirely hold and some of the basalts and ultramafics mapped by Macnab (1967) undoubtedly form part of the Papuan Ultramafic Belt here thrust clear across the gravity low. Rocks associated with the belt appear to be terminated against normal faults in the vicinity of the main gravity gradient, but may underlie the Lower Miocene volcanics further south. The gradient is the dominant feature of the southern end of profile MUSA and, as is shown in the next section, can be interpreted as being due to a roughly uniform plate of denser basic rocks overlying and abutting against normal continental crust. The various age relationships within what must in fact be a very complex basaltic sheet are not of course, susceptible to gravity analysis and

in fact the provenance of a given basaltic outcrop is also very difficult to determine in field mapping.

South of the gradient, and as far east as the 150th meridian, the Bouguer Anomaly map is relatively featureless and can be adequately accounted for by variations and compactions within the basaltic sequence. The geology of the province has been established at a reconnaissance level by Davies et al. (1968), and comparison with their map shows that local highs, somewhat suspect in themselves in that they are often suggested only by a single gravity reading, are associated with syenitic intrusions. Further east, in the region centred on the Ulo Ulo gold mine south of the head of Milne Bay, a much larger gravity high is also associated with igneous intrusions. The central part of the high encloses three separate intrusive outcrops, the largest a major gabbro, the Mila Gabbro, the second a smaller similar body with minor associated acidic rocks and the third a syenite with minor gabbro. The gravity pattern here indicates that these outcrops are part of a single intrusive stock, and the relationship of the syenite to the gabbro where these outcrop together suggests that the former is simply a late stage differentiate. Although Davies (pers. comm.) regards the presence of the potash rich syenites as indicative of the existence of continental rocks beneath the basalts, this seems an unnecessary hypothesis, at least on these grounds, since trachytic lavas are common late stage extrusions on oceanic islands. The Milne Bay intrusion was probably one of the main feeders for the lava outpourings that are now exposed at the eastern end of the Papuan Peninsula, and the syenites may mark similar sites; a minor, poorly defined high is also associated with the gabbro on the East Cape Peninsula, and extends east to include the unmapped Nuakita Island.

Very steep gradients occur on relatively small amplitude anomalies at the head of Milne Bay. The indicated strong near-surface density contrasts are almost certainly due to rugged topography of the upper surface of the hard, probably gabbroic, base beneath the Recent alluvium.

East of the Milne Bay high and centred about the north shore of Mullins Harbour is an extensive region of relatively low gravity. A narrow trough, coinciding with the coast and presumably infilled with light unconsolidated material is indicated by the steep gravity gradients, suggesting that the northern margin of the inlet was originally controlled by normal faulting accompanying a major downwarp. Although the present day coastline is very irregular, the bedrock outcrop pattern (Davies et al., 1968), if the gabbros are ignored, is that of a parallel sided trough rather similar to Milne Bay. The remainder of the gravity low is roughly co-extensive with outcrop of the Suen Beds, Lower Miocene limestones and volcanogenic sediments. A second relative gravity low, defined only at its edges, coincides with Milne Bay and its extension as far east as the Gallows Reef complex at 150° 15'E. The association of a quite acute minimum with this latter feature is interesting; as noted in the next section, the majority of similar reef complexes are disposed about a central gravity high due to an intrusive core.

Milne Bay and Mullins Harbour would both seem to be zones of subsidence bounded by steep normal faults. If the extension theory is correct such regions are to be expected in Eastern Papua, and it seems likely that these two in particular are closely connected. It also seems likely that the Ulo-Ulo gabbroic high is associated with the opening of the rifts and with the offset between them; as noted above, a part of the intrusion forms the only hard rock outcrop in the Mullins Harbour depression and the outline of the gravity high in and near Milne Bay is scarcely affected by the existence of the graben. The evidence is by no means conclusive; Mullins Harbour may not be a simple, straight sided depression and the gravity anomaly due to a pipe-like body of fairly uniform cross section is not necessarily markedly disrupted by near vertical faulting. However it seems reasonable to suppose that the intrusion is related to the zone of shear that

existed between the heads of the grabens during their formation and in part post-dates the subsidence. The roughly linear East Cape-Nuakita high paralleling Milne Bay probably marks the site of a major intrusion controlled by the rifting which allowed subsidence to take place.

Towards the south coast of the Papuan Peninsula, Isostatic anomalies become less positive and Bouguer anomalies increase. The latter pattern is characteristic of the transition from continental to oceanic crust, the former of transition from a gravitationally anomalous region to one in equilibrium.

6.2 The anomaly maps: marine areas

Considerable difficulties arose in contouring the off-shore gravity field because of the extremely irregular distribution of data points; this problem has already been noted as occurring in parts of the mainland but is there found in a much less acute form. Apparent incompatibilities between the different sets of data were also encountered, so that in areas where good coverage has been obtained using more than one source rigorous contouring may lead to tight flexures and closures which seem unlikely to be real features of the actual gravity field. In particular readings made on the U.S.N. Shoup have been frequently disregarded in areas where their inclusion would lead to the assumption of almost impossibly high gravity gradients.

A further factor to be considered is that, in an area in which less than one twentieth of the surface is above sea level, an island is in itself an anomalous feature, and trends deduced from onshore measurements can seldom be justifiably extrapolated very far from the coast. In this respect at least the situation in Eastern Papua is surprisingly tractable, and a large number of features detected or deduced from island measurements have had their existence confirmed by the marine surveys.

In the map of Simple Bouguer Anomaly (Map 2), an attempt has been made to contour the data (excepting only some of the more bizarre results from the Shoup) without interpretative smoothing. This map and the Free Air Anomaly map (Map 1) also include results from a much wider area than do the Maps 3 and 4 (Extended Bouguer and Isostatic Anomaly) in which detailed terrain corrections have been applied. In all maps except that of Free Air Anomaly, which contours a smoothed and filtered field, dashed lines have been used to indicate the possible position of contours in areas for which little or no reliable information exists.

The dominant feature of the Bouguer Anomaly Maps in the offshore area is the broad high associated with the central depression of the Woodlark Basin. Since marine Bouguer Anomalies are calculated by 'infilling' the sea with normal density material, high values are almost inevitably obtained in deep water areas, where Free air anomalies tend to be close to zero, and the actual significance of the pattern can be determined only by model studies or isostatic calculations. In the present case the Isostatic Anomalies of the central basin are also positive but are of course much smaller in amplitude; the maximum value is +78 milligals, as opposed to an Extended Bouguer maximum of +256 milligals. The Isostatic Anomaly Map (Map 4) would appear at first sight to indicate considerable over-elevation or abnormally thin crust in the central basin, but it must be remembered that the Airy assumption of compensation taking place at a single density discontinuity is not necessarily appropriate. If, as seems likely to be the case at active ocean ridges (c.f. Talwani and LePichon, 1969, p. 346), compensation is attained by a deficiency in mass over an extended column of material, the Airy anomalies will be positive even if equilibrium exists. In eastern Papua the highest Isostatic Anomaly values are observed not within the Woodlark Basin but along the northern flanks of the Woodlark Rise; it has been suggested (Osmaston, pers. comm.) that the flanks of zones of sea

floor spreading should be elevated above their isostatic datum, and if the Woodlark Basin is in fact such a zone it is perhaps to be expected that one at least of the bounding ridges will be out of equilibrium. Another consideration is that if the Woodlark and Pocklington Rises are actually rifted fragments of a former elongated continental or geosynclinal block, the compensating masses at depth may have been apportioned unequally during the break up. The fact that the Woodlark Rise is seismically active and the Pocklington Rise is not is in good agreement with the observed isostatic pattern of offshore Eastern Papua.

At least two of the major islands appear to have been formed by crustal disturbances which have resulted in significant distortions of the gravity pattern. One of these is Rossel, where the abrupt, almost right angled southward swing in the contours is in marked contrast to the shallow, undisturbed low which characterises the geologically rather similar Sud-Est Island, to the south-west; clearly there are strong structural reasons, indicated also by the bathymetry, for the absence of islands on the rise beyond Rossel. The flexure in the contours appears to be a regional feature, but is to some extent mirrored in the geology of the island, which recent mapping (Smith and Pieters, 1969) shows to consist of an anticlinal core of low grade schist flanked by pre-metamorphic meta-gabbro and minor ultramafics. However, strict correspondence with geology would require a minimum centred over the island, rather than the observed opening of the contours towards Sud-Est.

A somewhat similar flexure and the occurrence of a roughly meridional trend on Woodlark Island can be correlated more directly with the island's volcanic suite. Non-coralline rocks crop out only in the central and central southern part of the island and, as noted in Section 5.2, the detailed bathymetry both to north and south is suggestive of normal faulting, with downthrow to the east. The decrease in Bouguer Anomaly from

west to east across the island is consistent with such movements, although the pattern is complicated by minor closures possibly associated with concealed intrusions.

A notable feature of the gravity field along the Woodlark Rise is that the minimum values of Bouguer Anomaly are associated not with the rise crest, as would be expected for a homogenous isostatically compensated feature, but along the southern flank. West of the coral wall which defines the western bathymetric limit of the basin proper, the minimum develops into a major trough-like feature, probably indicative of a localised sedimentary basin (cross section TROBRIAND, Section 6.3). If extension has taken place in the Woodlark Basin the occurrence of a gravity minimum is scarcely surprising, since rapid sedimentation and possibly massive slumping from the rift walls would be expected.

The gravity pattern of the Woodlark Rise at its simplest is considered in the analysis of cross-section EGUM. The simple pattern is disrupted not only on Woodlark Island itself, but just to the east, along the line of bathymetric lineation noted at the end of Section 5.2. However this feature does not seem to be otherwise reflected in the admittedly rather sporadic marine gravity data, and so may be merely a coincidental alignment of a number of diverse minor structures.

A further linear gravity depression occurs in the outer flank of the Woodlark Rise just north of the Trobriand Islands. This is due to sediment fill in the known trough extending south and east from a junction with the New Britain Trench in the Huon Gulf.

A number of minor gravity highs scattered through the basin are due to the central core of dense intrusive rock within a predominantly extrusive volcanic cone; a good example is the high centred just south of the undoubtedly volcanic Panapompom Island in the Deboyne Group. The Conflict Group is also marked by a tight contour closure, centred just

on the present southern reef, and much larger anomalies occur in the vicinity of the Engineer Group and the Amphletts, both of which may possibly be remnants of major caldera collapses. Surprisingly Egum Atoll has less effect on the contours; in part this is probably due to the existence of a very steep regional gradient across it, which tends to mask the smaller local anomaly, but in addition the submerged mass is probably large enough to command fairly complete compensation.

The gravity pattern on Misima Island can only be described as confused. With such a narrow slice of rock confusion is almost inevitable, and at least the geological difference between the high grade western part of the island and the lower grade east appears to have gravity expression. The high nosing into the east of the island is somewhat unexpected and although a number of explanations can be advanced, none can readily be confirmed.

The simplified gravity pattern of the Pocklington Rise, as developed just west of Sud-Est Island, is discussed in the next chapter (cross section SUDEST). Between Sud-Est and the Papuan Peninsula the pattern has been very much complicated by volcanic activity.

6.3 The cross sectional analyses

The six gravity profiles here discussed have been measured across areas of Eastern Papua which are of considerable geological importance and in which the Bouguer contour pattern indicates that the two dimensional assumption may be made with a fair degree of confidence (see discussion, Chapter 3); fortunately the major structures of the region are all markedly elongated so that insofar as quantitative gravity methods are applicable at all they may be applied within the framework of two dimensional formulae. Since all potential field data are inherently ambiguous, in that the distribution of field sources cannot be uniquely determined from field

measurements, gravity methods are of most use in assessing the viability of structural hypotheses already formulated on other grounds. The approach adopted here has been to take models based on such hypotheses and controlled by outcrop data and use the gravity observations to determine additional necessary constraints. A model can be definitely discarded only when such constraints are in direct conflict with other requirements, but in these cases at least a valid answer to a geological question can be obtained gravimetrically. More commonly, the gravity data bear only upon the balance of probabilities of different models.

It should be noted that, although only a single model cross-section is shown for each of the profiles analysed, several thousand models were generated and several hundred examined in some detail in the course of this investigation. Thus, even though with complex models involving a large number of polygon corners the effect of simultaneous variation of position of several of these may not be intuitively obvious, in the cases discussed the effect of the possible changes considered have to some extent at least been studied. One major point,however,which has not been treated in great detail is the degree of isostatic compensation existing. In all the calculations it has been assumed that, where compensation occurs, it is wholly of the Airy type, based on changes in level of the Moho. This assumption is supported by the known pattern of increasing Moho depth beneath both the Papuan Peninsula and the offshore rises reported by M. Ewing et al., (1970) and Furumoto et al., (1970). In the second of these papers however it is also shown that in some places,and notably in the central Woodlark Basin, the seismic velocity along the Moho refractor is abnormally low (7.3 - 7.9 km/sec),which suggests that the mantle density is also low. It seems very probable that some element at least of Pratt type compensation exists in Eastern Papua, and although this has not been introduced in any of the calculations, it must be accepted that, in view of the limited width of all the major structures, perfect regional compensation may exist in all the

cases considered, provided only that some of the compensation takes place within the mantle.

Another feature of the cross sections to which objection might be made is that the density contrasts between standard continental crust (of thickness 30 km) and some major bodies of considerable vertical extend are regarded as constant. Although this may introduce some errors, it must be remembered that the density structure of the crust is still imperfectly known, while the increases in pressure and temperature which tend to result in higher crustal densities at depth may act in a similar fashion on the anomalous bodies both by simply compaction and by such processes as the dehydration of serpentine.

In each profile the agreement with the calculated field is to better than 5% at the point of maximum discrepancy. More exact correspondence could have been attained relatively easily by increasing the complexity of the models, either by introducing further geologically plausible bodies or by adding to the number of corner points on the polygons actually used. This was not done, partly because some at least of the discrepancy is likely to be due to departures from uniform density or strict two-dimensionality, but chiefly because the increased detail in the more specialised models produced in this way would tend to obscure the main general features which alone are likely to be of importance at this reconnaissance scale. Most of the models shown can be modified in several major ways whilst still retaining an acceptable fit, and much of the following discussion is devoted to consideration of these possibilities.

Cross section IOMA

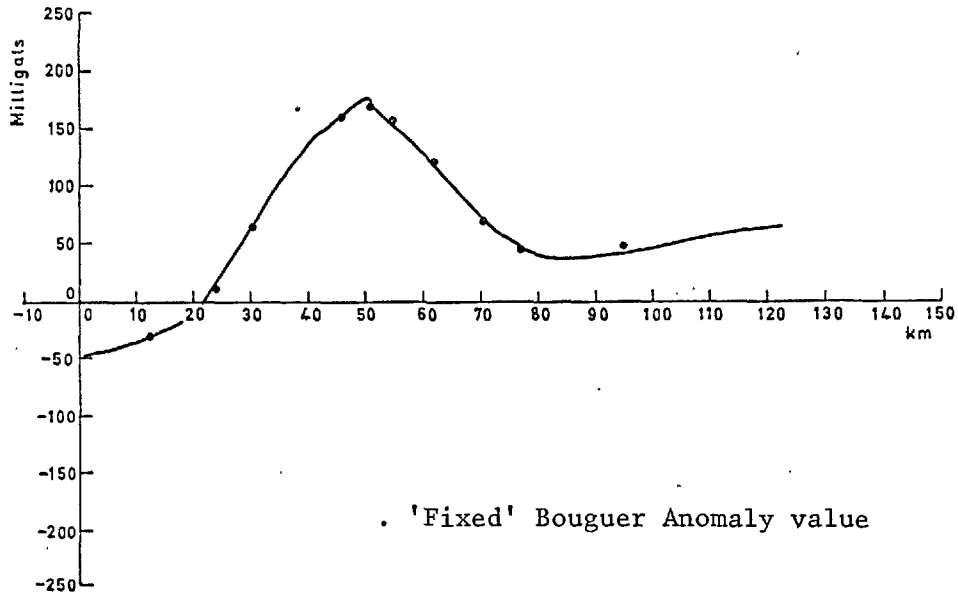
The largest of the positive anomalies associated with the Papuan Ultramafic Belt, that over the Bowutu Mountains, has not been treated analytically since it has been so far defined only in the relatively narrow crestal zone coinciding with these mountains and the shape of the

equally important 'wings' is still unknown. The profile IOMA, taken along a line crossing the second largest of the positive peaks, is therefore crucial in the examination of the overthrust sheet hypothesis, and an attempt has been made to satisfy the observed field using such a model. This repeats to some extent the approach used by StJohn (1967), but differs in that it is assumed that the ultramafic belt is overlain to the west not by normal continental crust but by light sediments laid down since overthrusting. This follows a suggestion made by Davies (1970, p. 5) that 'instead of sialic crust there are Upper Tertiary sediments of greater thickness and lower density than StJohn has allowed', and is also in accord with the seismic evidence (Furumoto et al., 1970) for the oceanic nature of the Solomon Sea, which would seem to preclude StJohn's solution, at least in the north-western part of the belt.

As can be seen in Figure 6.1, the gravity profile IOMA is almost coincident with the aeromagnetic profile AA selected by the Compagnie General de Geophysique (1969) for their interpretation of the structure of the ultramafic belt. It is interesting that these two independent analyses of unrelated data have resulted in very similar final models, with, in both cases, the ultramafic rocks being very thin beneath their main area of outcrop. The aeromagnetic interpretation that this 'lip' of dense rock is a transcurrent fault slice lying between the Gira and Owen Stanley Faults (see Section 5.3) is certainly consistent with the gravity pattern, but in view of the very similar structure deduced for the cross section MUSA below, it would also seem possible that the overthrust simply flattens near the surface. The field evidence for near vertical dips on the western side of the Bowutu Mountains (Davies, 1970) is probably due to purely local conditions caused either by vertical isostatic adjustments of the sialic relative to the ultramafic rocks along the Owen Stanley Fault Zone or by transcurrent movements along the Gira Fault, there coincident with that zone.

The model shown in Figure 6.3 emphasises a very important feature of the Papuan Ultramafic Belt. Although the anomalies observed are very large by normal standards, the main difficulty encountered in reconciling the outcrop and gravity patterns lay in arriving at sufficiently low peak amplitudes. As one step in this direction, the density contrast between the predominantly ultramafic part of the belt and normal continental crust was assigned a value of .4 gms/cc, in place of the.45 gms/cc used by St John (1967). This lower value seems reasonable in view of the partial, though generally slight, serpentinisation observed and the presence of gabbroic intrusives within the ultramafic sequence, and its adoption is made almost mandatory, at least for the upper part of the belt, by calculations of the gravity gradient to be expected along the Owen Stanley Fault zone; the ultramafic rocks, if of bulk density greater than 3.1 gms/cc, would have to be implausibly thin. The density reduction for the ultramafics is compensated in part by the assumption of a positive density contrast for the whole of the mafic section, rather than merely for the intrusive part. This assumption is made since, if the belt were originally part of a normal oceanic crustal layer, extrusion of lavas must have taken place in relatively deep water and they would be expected to have densities in the region of 2.9 gms/cc (c.f. Rose et al., 1968).

The model shown in Figure 6.3 is of course schematic only, but a number of features in addition to the comparative thinness of the ultramafics beneath their area of outcrop seem to be well established. It proved to be simplest, in fitting the observed to the calculated field, to assume the slice of rock caught up in the Owen Stanley Fault Zone to have a greater than normal density, which might be expected of pressure metamorphosed basalts and limestones, and not a lower density as suggested by St John (1967). The incompleteness of Airy type isostatic compensation also seems



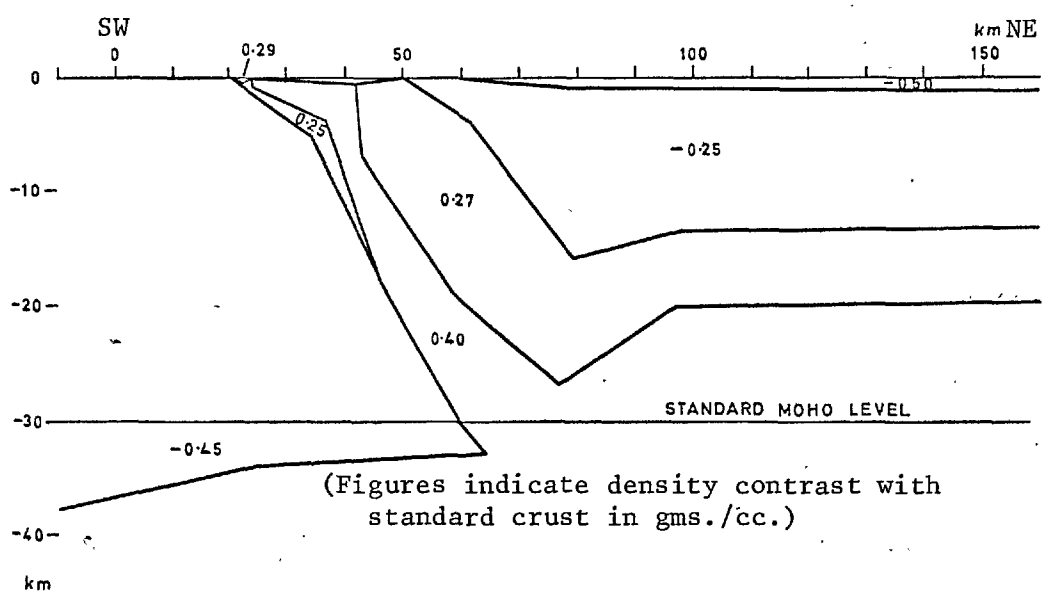


FIGURE 6.3 Cross-section IOMA; computed curve measured Bouguer Anomaly and model.

confirmed, the calculated depression of the Moho being insufficient to support even the mass excess represented by the sub-geoidal part of the belt, let alone the exposed topographic mass of the Ajule Kajale Range.

In the north-eastern part of the cross section the areas occupied by the various rock units, and their relative density contrasts, can be varied within much wider limits. The ultramafic belt as shown is overlain by sedimentary layers of density deficit .5 gms/cc and .25 gms/cc, with a total thickness of between twelve and fifteen kilometres. Two layers are used since the density of sedimentary rocks generally increases with age and depth of burial, but it is not intended that the change used should be correlated with any particular horizon or interface within the sediments; in all probability sedimentation has been continuous and reasonably uniform since the emergence of the Papuan Peninsula. The density deficit of .25 gms/cc is probably too high for the very lowest layers of the sedimentary column, where compaction and metamorphism may have produced rocks with little if any contrast with normal continental crust; however it may equally be argued that at these depths the basaltic layer of the ultramafic belt may also have a more or less 'normal' density, and the actual boundary of the two units could well be as shown.

A probably more important point is that the slope of the thrust sheet has been made relatively gentle,and the thrust sheet itself relatively thick,mainly to account for the increase in gravity field towards Cape Ward Hunt. However, as has been noted in the general discussion of the gravity pattern in this area, the gravity high may be due to a comparatively localized basement ridge and not part of a regional trend. The introduction here of an additional polygon with a positive density contrast, as required by such a hypothesis, would necessitate a corresponding reduction in the thickness of the ultramafic belt, at any rate at depth. As shown,

the modelled thrust sheet has a total thickness of some twenty kilometre, of which about eight belong to the ultramafic and the remainder to the feldspathic suites; this latter amount is very much what would be expected for an exposed slice of oceanic crust. Because of the flattening of the dip of the thrust sheet or possible faulting which result in the existence of the 'lip' shown in Figure 6.3 the outcrop pattern gives a rather false impression of the relative importance of ultramafic and mafic rocks in the belt as a whole. The total length of the supposed thrust sheet from the junction with the mantle to the outcrop is about forty kilometre and the average dip is about 45°.

The object of the computations carried out was to investigate the constraints imposed by the gravity data on the overthrust sheet model and not to consider the wide range of possibilities involving detached sheets or intrusions. However a number of such models were generated and in particular it was found that where the thrust sheet was completely detached from the mantle, dipped much more shallowly than shown in Figure 6.3 and was associated by faulting with the basalt exposures on Cape Ward Hunt, an acceptable fit with the observed gravity field could be readily obtained. In such cases the mafic-ultramafic rocks apparently overlie layers of 'normal' crust and are of markedly non-uniform cross section, 'bulging' below the area of maximum positive Bouguer Anomaly. Although the model can be converted into an overthrust sheet type quite simply by postulating a junction with oceanic crust well to seaward of Cape Ward Hunt, the mechanical considerations discussed in the next chapter make such a conclusion unacceptable. Although consistent with the mantle overthrust hypothesis, therefore, the cross section shown in Figure 6.3 cannot be said to provide positive confirmation of it.

The possibility of density variations within the Owen Stanley Ranges has not been considered in preparing the models. Although the presence of major intrusions of intermediate composition in these mountains makes the existence of large density contrasts likely, the lack of data from the area precludes quantitative studies.

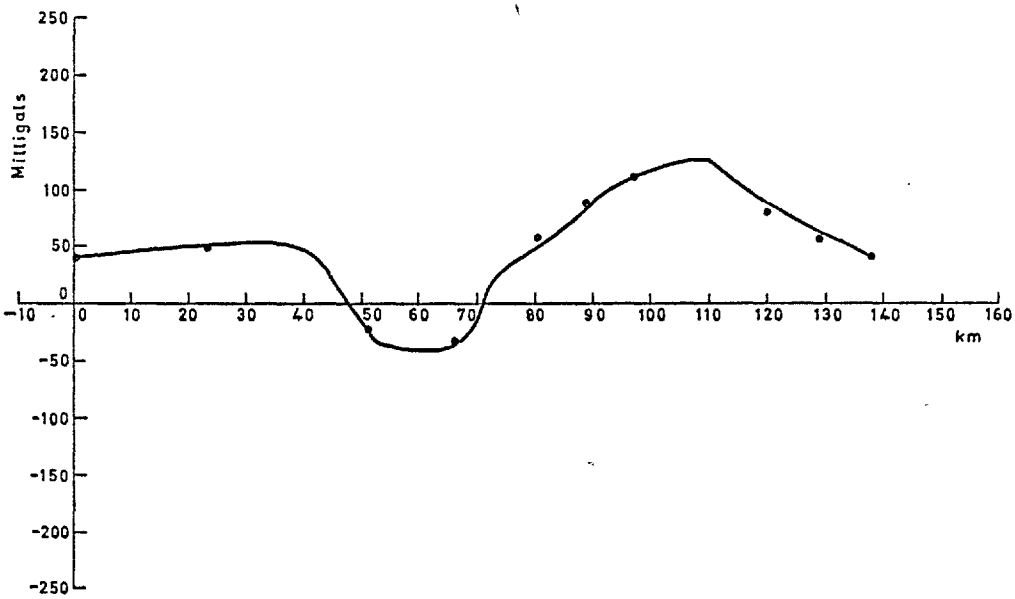
Cross section MUSA

This cross section also is taken along a line through a peak anomaly of the Papuan Ultramafic Belt, but in this case the whole of the low to the south has been defined by gravity readings whereas the shape of the profile north of the peak is almost unknown. The total length of the thrust sheet in this model is over eighty kilometres, and, if the detached block south of the Musa valley is included, over a hundred. As might be expected in view of the smaller peak values of the MUSA, as opposed to the IOMA, positive anomaly, the observed field is satisfied most simply by use of a model involving a thinner thrust sheet, consisting of about 7 km of predominantly ultramafic rock and a further 7 km of mafic intrusives and lavas. As modelled the sheet is overlain in part by normal density material and in part by very much lighter sediments with a density deficit of .3 gms/cc. A thrust sheet very much thicker at depth would be permissible if either the thickness or the density contrast of the low density layer were made larger, but the allowable thickness of ultramafic rock near the surface is constrained quite strictly by the gravity data and cannot be very greatly increased. Thickening of the overthrust towards its root zone is, of course, quite probable, and is in fact shown as occurring in the diagram given by Davies (1968a) and reproduced here as Figure 7.2; however if the thrust sheet is attenuated markedly beneath its northern outcrop area such attenuation would be expected to continue at a relatively uniform rate, and it is rather surprising that any fragments of ultramafic

rock have survived on the southern side of the Musa depression. In the model shown here the rock underlying this southern ultramafic outcrop is allotted a positive density contrast of only .2 gms/cc, smaller in fact than that given to the entirely mafic lavas to the south. Although it is possible that the ultramafics in this area are in fact both thinner and denser than shown, the comparatively high degree of serpentinisation observed argues that the present model may be reasonably appropriate.

A density contrast of .45 gms/cc for the ultramafic part of the main belt and .25 gms/cc for the overlying feldspathic rocks has been used in the analysis. This value for the ultramafic rocks, .05 gms/cc higher than for the corresponding polygon in cross section IOMA, has been chosen not on any theoretical grounds but because agreement with the observed gravity field is more readily attained. Density variations of this order are to be expected along the length of a complex extended body such as the Papuan Ultramafic Belt.

The Musa Valley itself is considered to be underlain by a body having a considerable extent in depth and a small density contrast with normal continental crust. Wide variations in depth, shape and density contrast are allowable. Relative vertical movements, probably of an isostatic nature, are assumed to have taken place between this block and the main thrust sheet, resulting in the near vertical contact shown; presumably the ultramafic rocks which once overlay the low density material were raised above the remainder of the belt and subsequently eroded away. On this hypothesis the Musa depression is presumably the result of differential erosion; comparison with Mt Suckling to the east, where some granite and quartz veining are known, suggests that the low density is due to a granitic batholith. In the course of iteration a satisfactory model was also produced in which the Musa depression was apparently a graben infilled with



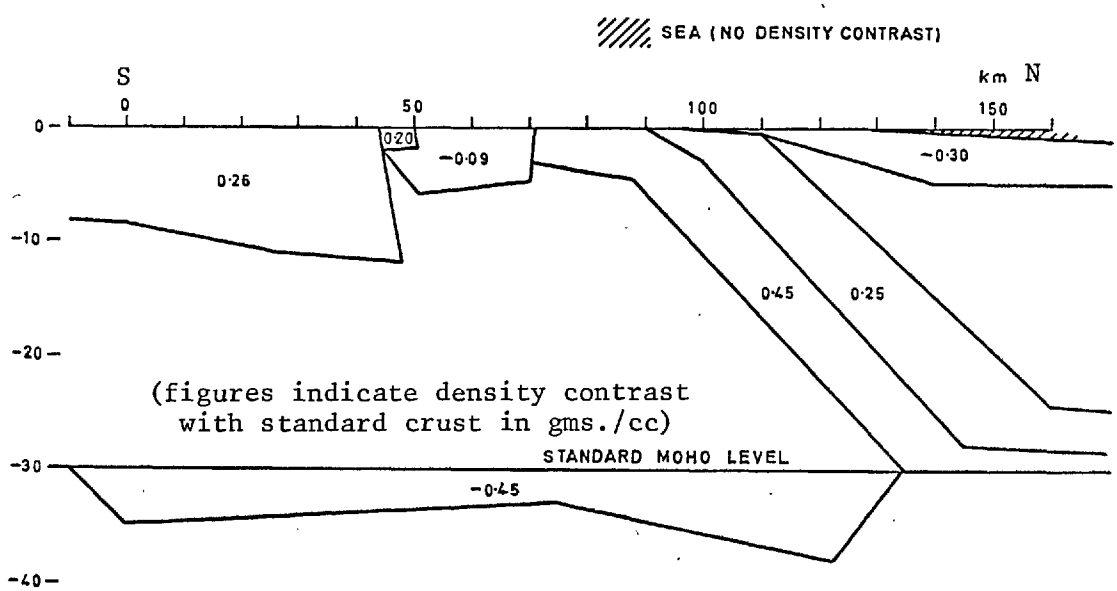


FIGURE 6.4 Cross-section MUSA; computed curve, measured Bouguer Anomaly and model.

very light sediments, but, as noted in the regional discussion (Section 6.1) the occurrence of the deepest part of the gravity low at Mt. Suckling argues against such a hypothesis.

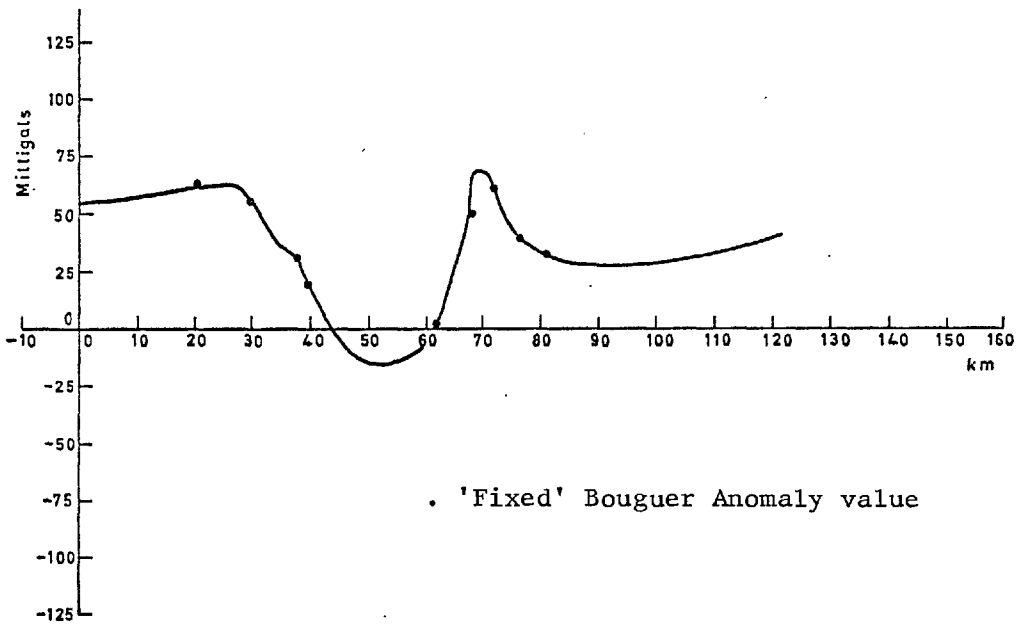
South of the Musa lies the basaltic province of Eastern Papua, represented here by a great plate of dense material eight to ten kilometre thick. The underlying depression in the Moho is sufficient, on the Airy assumption, to compensate for the sub-geoidal mass excess but not for the excess in the basaltic mountains. Full Airy compensation could be reached if the dense layer were very much thicker but this seems geologically unlikely; the comparative lack of seismic activity in this province (Figure 5.2) suggests a degree of stability which, as discussed earlier, is probably attained in part via a lowering of mantle density. The ultramafic thrust sheet, on the other hand, would appear to be slightly overcompensated.

The principal object of the analysis of this cross section, as with cross section IOMA, was to determine limits applicable to the overthrust sheet hypothesis, and because of the absence of any suggestion of major transcurrent movement between parts of the ultramafic belt in this area, the MUSA model is probably the more satisfactory for this purpose. The intrusive or detached sheet possibilities were again not investigated in any great detail, but the absence of gravity data offshore to the north allows considerable latitude in both these cases. A detached 'pod' model in fact very readily fits the measured profile.

Cross section VOGEL

The most striking feature of the profile VOGEL is the small but intense and steep sided gravity high on the Cape Vogel Peninsula. Because of their position, roughly along strike from the easternmost known outcrops of the Papuan Ultramafic Belt, and because of their unusual mineralogy, Dallwitz et al., (1967) have suggested that the lavas cropping out in the central part of the peninsula are genetically related to the rocks of the belt. Because of this a dipping sheet model has been used in modelling the subsurface geology of the peninsula, with the final result shown in Figure 6.5. It is obvious that by assuming a slightly thicker sedimentary section to exist in the northern part of Goodenough Bay a good fit could be obtained using a much more symmetrical high density body, and it cannot really be said that there is any gravitational evidence for a seaward dip. On an extension hypothesis a simple near-vertical intrusion might be expected, and this is certainly allowable. An interesting point is that, to explain the observed very steep gradients along the south coast of the peninsula, it is necessary to postulate a very large density contrast, of the order of .3 gms/cc with normal crust and thus of .75 gms/cc with the Goodenough Bay and Cape Vogel sediments. While this is still quite a long way from the typical peridotite density range, it does suggest that the outcropping pillow lavas are underlain at shallow depth by very mafic intrusive rocks.

To the south of Goodenough Bay, which is devoid of gravity readings, outcrops on the Papuan Peninsula are dominantly of basaltic pillow lavas similar to those in the southern part of profile MUSA. The gravity analyses again suggest that the mafic section has a thickness of eight to ten kilometres and can be locally compensated on the Airy system only in respect of the sub-geoidal mass excess. However the sea water and



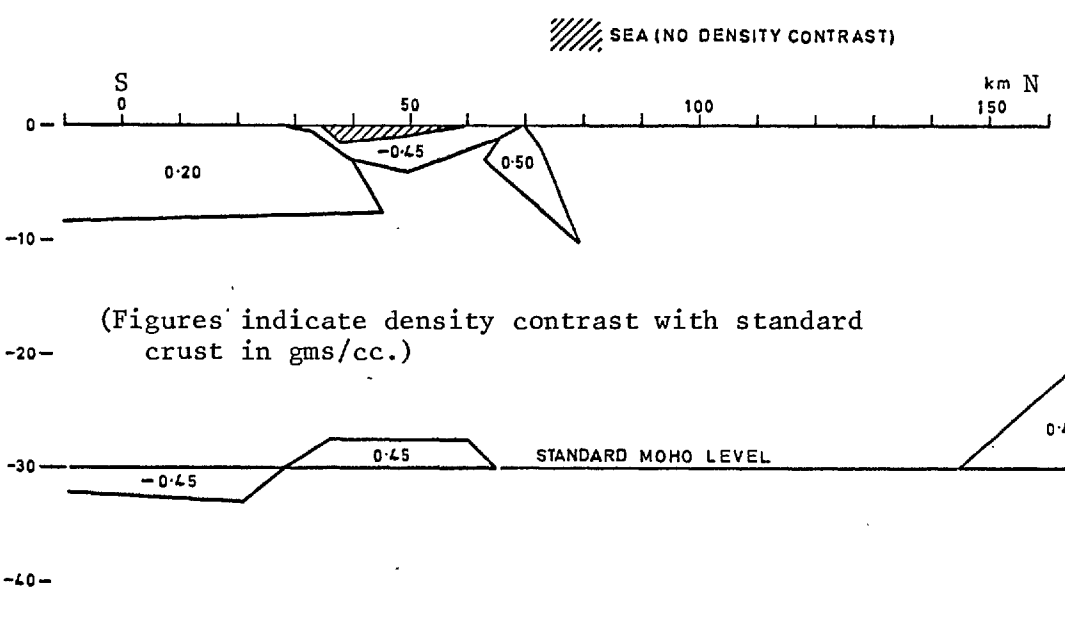


FIGURE 6.5 Cross-section VOGEL; computed curve, measured Bouguer Anomaly and model.

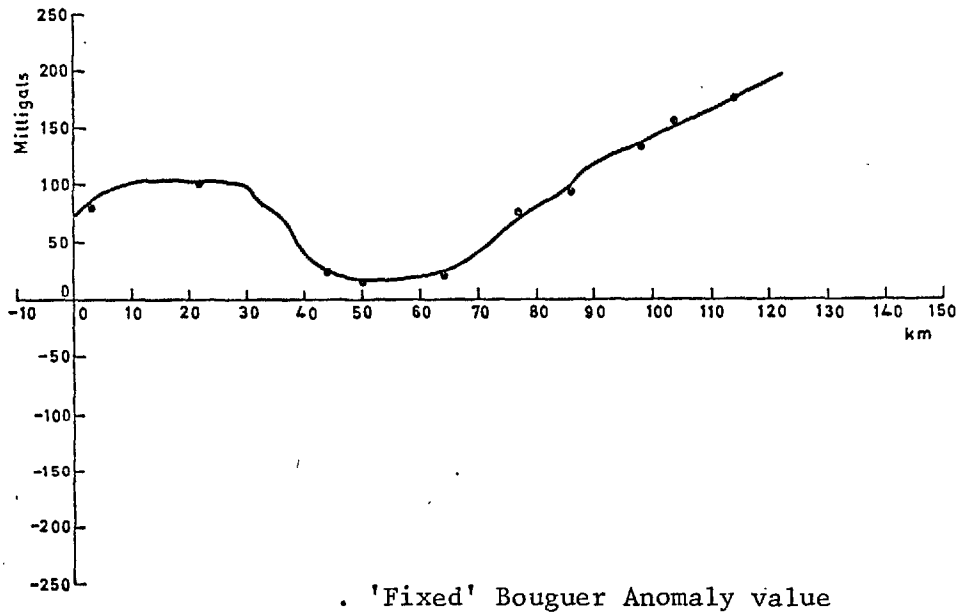
underlying sediments of Goodenough Bay represent a mass deficiency in the upper crust which does not appear to be matched by the rise in Moho level beneath and, although on the cross section as drawn the relative extent of bay and basalt appear very unequal, it must be remembered that a few kilometres only further east the two features are of approximately the same width. The probability that the Woodlark Basin is of extensional origin has already been discussed in Chapter 5, where it was noted that such extensional movements are likely to occur at least as far west as the cross section now being studied. Under an extensional regime isostatic equilibrium should prevail, although if rapid movements are involved the compensation may not be locally exact. It would also be expected that an element of Pratt type compensation, the gravity effects of which are very similar to those of regional Airy compensation, would exist, with low density mantle underlying the actual zone of extension. The pattern observed,with blocks apparently over and under compensated adjacent to each other, is consistent with this hypothesis.

The depth of sediments shown in Goodenough Bay seems reasonable in view of its situation, surrounded on all sides by high standing, rapidly eroding terrain, and also in view of the thickness of the exposed sections of recently uplifted Plio-pleistocene sediments along the southern shore. The density structure within the sedimentary column is undoubtedly much more complex than that shown, but since the profile has not been defined across the bay itself, more detailed modelling cannot really be justified.

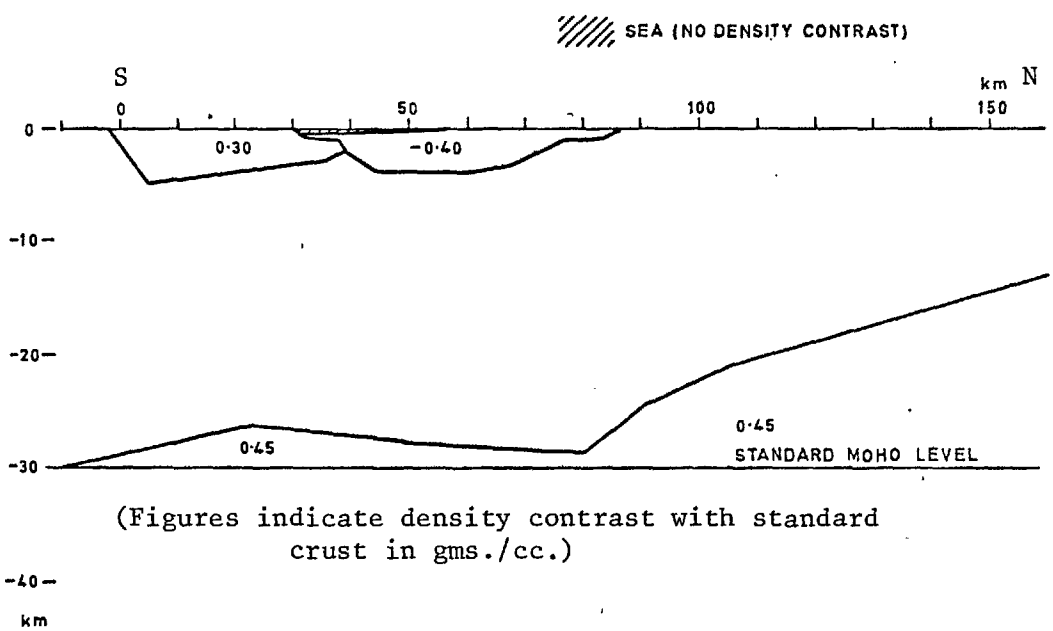
Cross section TROBRIAND

The main feature of interest in this profile is the very steep sided gravity low just to the south of the Trobriand Islands, both because of its bearing on the structural problems of Eastern Papua and because of the area's possible importance as a site of petroleum accumulations. In view of the large amplitude of the anomaly and the steep gravity gradients involved, the only possible explanation would seem to be the presence of a deep basin infilled with light sediments. Such a structure can best be explained as the result of extensional movements related to the opening of the Woodlark Basin, from which the sediments are separated by a continuation of the coral 'wall' which marks the eastern boundary of the Trobriand Islands. Whatever the origin of this wall, it would seem in this case to have acted as a barrier to transport of sediments from the main emergent masses of New Guinea and Papua into the Woodlark Basin, and the calculated great thickness of sediments ponded on its western side is therefore hardly surprising.

In the model the Woodlark Rise (Trobriand Island) is shown to be composed of normal continental crust, but the scanty outcrop data suggests that in fact much of the rise is built up of dense mafic igneous rocks. The adjustments required to satisfy the gravity data with such a model are quite simple; the density of the sediments south of the Trobriands can be increased to maintain a constant density contrast with a mafic upper crust, and the Moho can be depressed to compensate for the general increase in field levels thus produced. Only a small change in shape of the sedimentary basin polygon would be necessary. The modified model has the advantage that a rather more plausible degree of compaction in the sedimentary column would be allowable.



. 'Fixed' Bouguer Anomaly value



(Figures indicate density contrast with standard crust in gms./cc.)

FIGURE 6.6 Cross-section TROBRIAND; computed curve, measured Bouguer Anomaly and model.

The magnitude of the density contrasts between mafic and acidic igneous rocks do not seem to allow of a solution in which the gravity low is due to a light acidic intrusion. The only possibility of this sort would seem to involve the existence of a great ultramafic slab near the surface of the Trobriand Rise, which raises considerable structural problems in view of the essential continuity of the rise to Cape Ward Hunt, running behind the ultramafic belt in the Musa and Ioma regions.

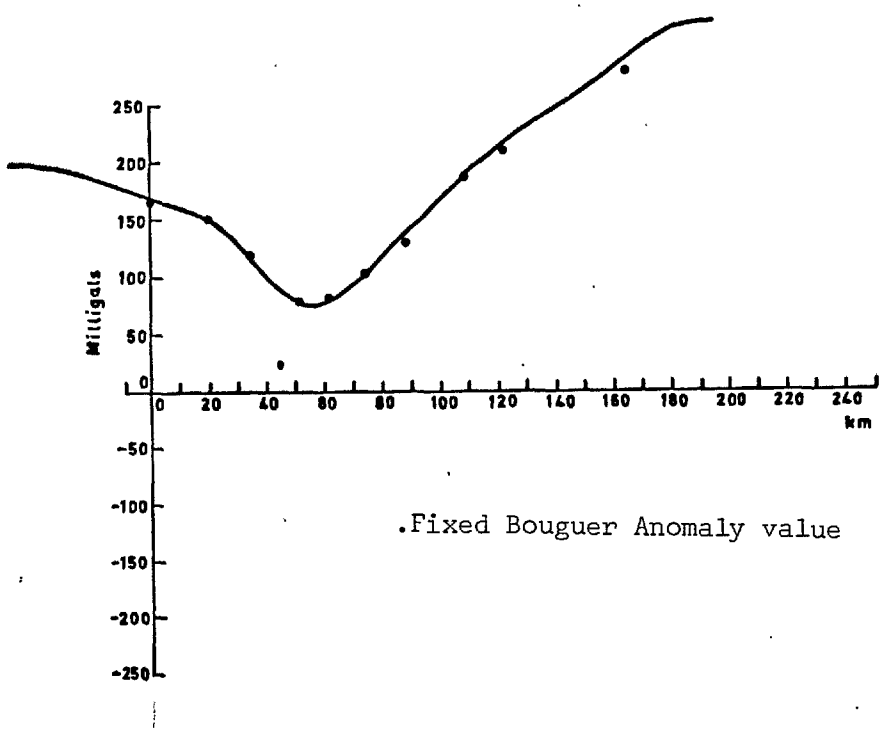
The presence of a large mass of high density rock is necessary to explain the observed gravity high in the vicinity of the Amphlett Group. The volcanics which make up the islands are mainly andesitic (Davies and Ives, 1964), but the gravity pattern suggests that they overlie more mafic rocks, possibly cumulates.

The increase of gravity at the northern end of the profile is the normal and expected consequence of crustal thinning towards the oceanic Solomon Sea.

Cross section EGUM

The two marine cross sections are based on much simpler models than those fitted to profiles defined by land measurements. In part this reflects a greater structural simplicity in the marine areas, but in the main is due merely to the poorer quality and less even distribution of the marine measurements. In the case of the profile EGUM an adequate fit between observed and computed curves has been obtained using a single upper crustal anomalous body together with a crust-mantle interface of varying depth.

An unexpected feature of the gravity pattern along the Woodlark Rise is that the minimum Bouguer Anomaly values do not coincide with the crest of the rise, as would be expected in the case of simple



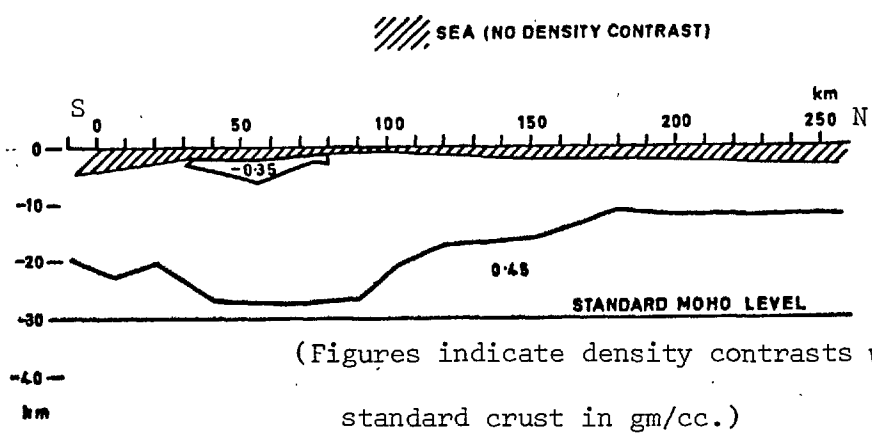


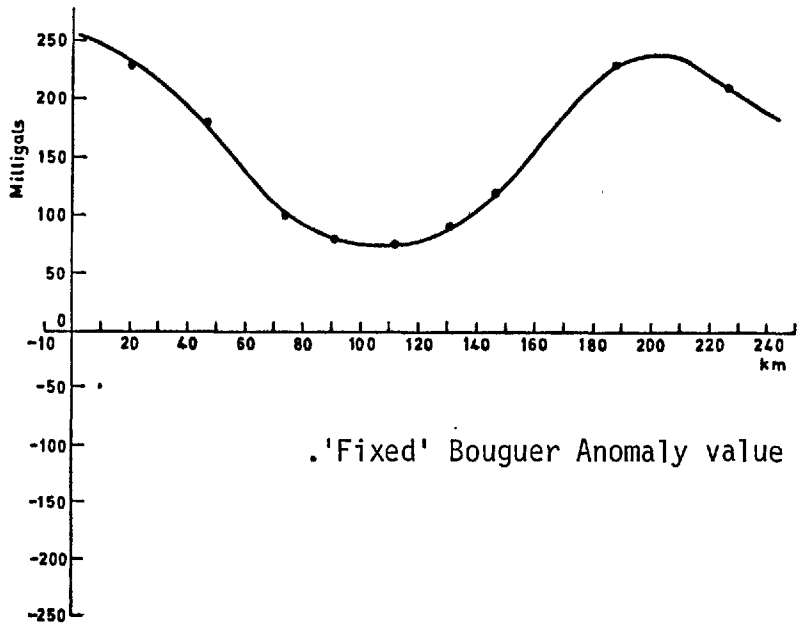
FIGURE 6.7 Cross-section EGUM; computed curve, measured Bouguer Anomaly and model.

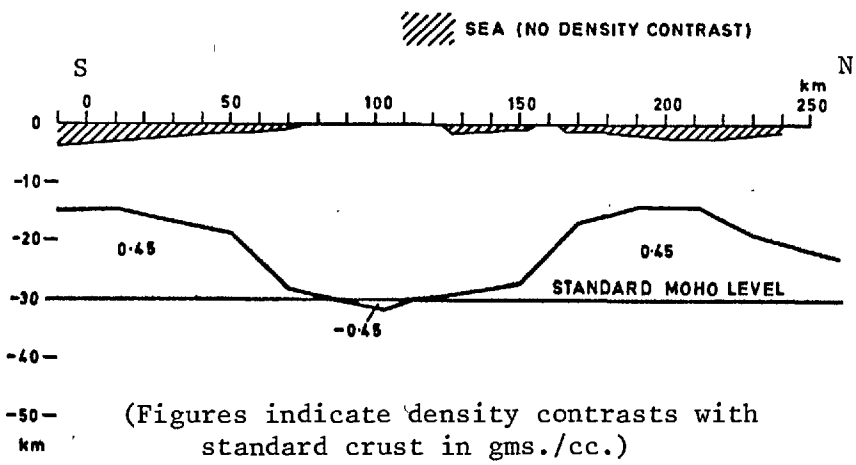
isostatic thickening, but are offset some way to the south. Moreover this minimum is too steep sided to be explained simply in terms of raising or lowering of the Moho, and a considerable block of low density material has been introduced to obtain a fit to the profile. More detailed calculations, based on a crust-mantle density contrast of .45 gms/cc, indicate that the Woodlark Rise as a whole is above its base level of isostatic compensation, even on a regional scale.

Such a geological structure can be simply explained by the hypothesis of an extensional origin for the Woodlark Basin (Section 5.1). Extension may be supposed to have resulted in the rifting apart of an elongated continental block which now survives principally as the Papuan Peninsula and the Woodlark and Pocklington Rises, and it is probable, if not inevitable,that in the splitting up of such a narrow slab the compensating mass deficits at depth would be apportioned unequally between the separating fragments. The present day seismicity of the Woodlark Rise may be due to subsidence of the under-compensated crust, and possibly also to the slumping of near surface masses off the unsupported wall of the rift. Such slump blocks, together with sediments derived from the emergent part of the rise, are probably the source of the gravity low and make up the low density polygon shown in Figure 6.7. As in earlier cases where sedimentary basins were hypothesised, a more complex density structure doubtless exists, but the sparsity of the data makes more complex modelling inadvisable.

Cross section SUD-EST

Fitting the field due to a two dimensional model to the gravity profile obtained just to the west of Sud-Est Island (Figure 6.8) proved very simple, in that it was necessary to assume only a Moho of varying depth. In part this simplicity is a result of the choice of profile





(Figures indicate density contrasts with standard crust in gms./cc.)

FIGURE 6.8 Cross-section SUDEST; computed curve, measured Bouguer Anomaly and model.

location, and the gravity field in some other parts of the Pocklington Rise is certainly much more complex. However these complicating features do not, in general, have any great lateral extent and are thus, at the most, of local interest; they are not, by their very nature, amenable to two dimensional model studies. The most interesting points to emerge from the calculations are that even on the Airy assumption the rise appears to be somewhat over-compensated, and that the centre of compensation apparently lies on the Woodlark Basin side of the rise crest. This agrees well with the evidence deduced in analysis of cross section EGUM for under-compensation of the Woodlark Rise, and evidence from elevation of coral reefs along most of the Pocklington Rise crest, for both elevation and tilting of the block. The greatest elevation of reef is seen on Misima Island (De Keyser, 1961), whilst the southern barrier reefs are now all below sea level. This characteristic of elevation to the north and subsidence to the south is, of course, also seen along the Papuan Peninsula, where the gravity pattern is complicated by other effects.

CHAPTER 7

CONCLUSIONS

In the preceding chapters it has been proposed that Eastern Papua, at least in Recent times, has been governed by an extensional tectonic regime. This conclusion, arrived at mainly on the basis of the seismicity and bathymetry of the area (Section 5.1) derives additional support from the surface geology and gravity pattern, although this further evidence is admittedly somewhat ambiguous; it has long been argued that extensional and compressive tectonics can give rise to very similar gravity patterns, the controversy over the nature of the East African Rift system being a case in point. However the extensional hypothesis has so far in this thesis been applied only to the continuing movements in the Woodlark Basin and the possible importance of tensional forces during the earlier history of the Papuan Peninsula has not been discussed.

Since marked uplift is a characteristic of the margins of both continental rifts and the central rift valley of the mid-ocean ridges, extension in the Woodlark Basin can be tentatively dated by relating the elevation and emergence of land masses in Eastern Papua to such movements; a late Miocene initiation and a spreading rate of about 1 cm/year near Woodlark Island, which seems reasonable in view of rates calculated for ocean spreading (LePichon, 1968), would be deduced on this basis. This phase of expansion could therefore not have affected the formation of the rocks of the Papuan Peninsula and the larger islands, which are dominantly Cretaceous to mid-Miocene in age, and in particular could not have been a control during the Eocene or late Cretaceous emplacement of the Papuan

Ultramafic Belt. Probably, however, the Woodlark Basin is only the most recently formed of a series of triangular rifted basins developed in the area; the Coral Sea basin is closed in many of the published reconstructions of a pre-Cretaceous Gondwanaland (Rod, 1967; Carey, 1958), and some workers on the geology and geophysics of New Britain are now proposing an extensional origin for the Solomon Sea (Barlow, pers. comm.). The possibility of repeated rifting along closely adjacent parallel or sub-parallel belts has recently been emphasised by Karig (1970), and his suggestion, for which he provides considerable observational support, that island arcs migrate by such a mechanism has been listed by Vine (1970) as one of the most important new hypotheses of the past year. Applied to Eastern Papua, Karig's ideas have the advantage of reconciling the occurrence of andesitic vulcanism and granodioritic intrusion, which are characteristic of island arcs and active continental margins, and therefore commonly accepted as indicative of compression, adjacent to features of roughly similar age which may be of tensional origin.

As was noted in the introductory chapter, the major geological problems posed by the Papuan Peninsula are those concerned with the origin and evolution of the Papuan Ultramafic Belt. Thayer (1969) included the belt in his category 'alpine sensu stricto peridotites', a group whose members are identified on the basis of chemical composition, association with less mafic rocks such as gabbros and tonalites, and evidence for tectonic emplacement at comparatively low temperatures. Many such bodies fall also within the "ophiolite" category (Steinmann, 1927) in common use among European geologists, although it must be noted that Thayer (1969) specifically denies any direct genetic connection between dolerites and pillow lavas, which are considered to be an integral part of the ophiolitic suite, and his "alpine s.s. peridotites". Use of the term

ophiolite frequently implies acceptance of the hypothesis that the entire suite was emplaced as an enormous differentiating lava flow extruded over oceanic crust on the margins of a geosynclinal depression, a mode of origin outlined most clearly by Aubouin(1965). Aubouin's analysis of the evolution of ophiolites, the so-called plutovolcanic hypothesis, is based on the observed field relationships of these rocks in south-eastern Europe, and is essentially independent of his reconstruction of the origins and evolution of geosynclines; Figure 7.2 is based on his proposed cross section through a freshly extruded ophiolitic mass of the Hellenic belt, but such a body, after uplift and erosion, could clearly give rise to outcrop patterns and gravity fields remarkably similar to those observed in the Bowutu Mountains and Ajure Kajale Ranges.

The "alpine peridotite" notation stands in contrast to the plutovolcanic hypothesis in that the belts of ultramafic rock are regarded as fragments of oceanic crust and upper mantle incorporated in the upper continental crust in solid or semi-solid state during orogeny. In its simplest form this idea reduces to one of mantle overthrusting, as proposed by Davies (1968a) for Eastern Papua. Figure 7.1 is an enlargement of the geological cross section and accompanying gravity profile (Simple Bouguer Anomaly) given by Davies in this paper, with symbols for rock types taken from Aubouin (1965) for ease of comparison with Figure 7.2. As the hypothesis has been accepted by many of those who have worked in Eastern Papua in recent years, and as it has been widely published (e.g. Dow and Davies, 1964; StJohn, 1967; Davies, 1968a; Thayer, 1969), it has been used as the basis of the gravity approach to the structure of the Papuan Peninsula, and in Section 6.3 overthrust sheet models are shown that are closely compatible with the gravity data. However these models (Figure 6.4, 6.3) differ in a number of important respects from the simple cross section

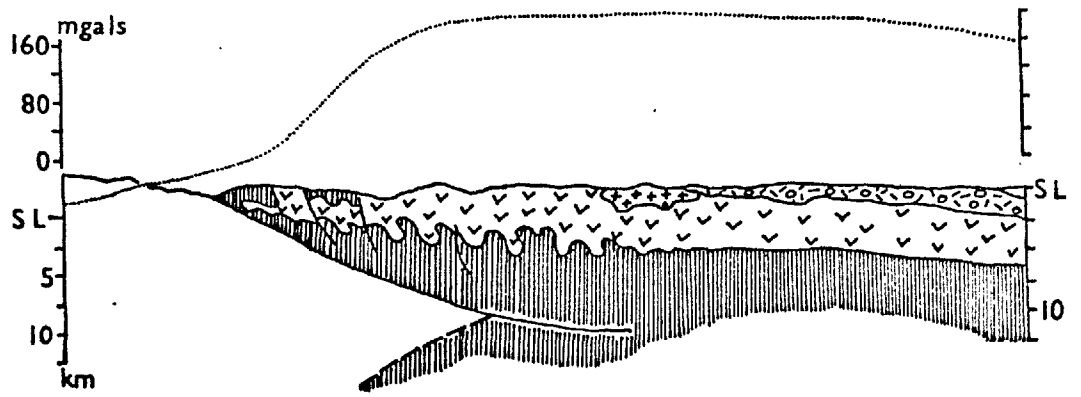


Fig 7.1 From DAVIES (1968a)

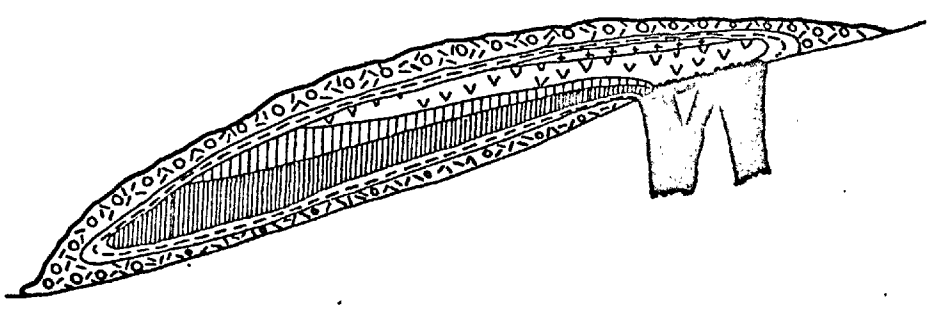


Fig 7.2 From AUBOUIN (1965)



FIGURES 7.1,7.2 Key: 1)"Feeder" 2) Peridotite 3) Pyroxenite 4) Gabbro 5) Dolerite 6) Tonalite 7) Pillow lava 8) Bouguer Anomaly Profile

shown by Davies, and it must be noted that although he included a gravity profile in the sketch, presumably as supporting evidence, the peak value of Bouguer Anomaly actually observed is only about a third of that required by the structure proposed. Although this figure is based on application of simple two dimensional formulae only to the cross section, and although the mismatch could be reduced by large departures from the conditions assumed in making this approximation, such departures would raise serious geological problems, since it is hard to envisage a mechanism able to shear off a sliver of crust and upper mantle with a width only of the same order as the thickness. While it would be inappropriate to base detailed quantitative arguments on a diagrammatic sketch of this nature, it can be shown that the structure of Figure 7.1 differs fundamentally from any structure that can be deduced on the basis of the gravity field.

A number of detailed theoretical studies of the mechanics of overthrust faulting have been published (Hubbert and Rubey, 1959; Hsu, 1969a) and, although the conclusions to be drawn have been the subject of some controversy (Hubbert and Rubey, 1969; Hsu, 1969b); it seems reasonably safe to apply the general principles to the mantle overthrust hypothesis. Calculations based on the model proposed for the Papuan Ultramafic Belt have shown (Butler, pers. comm., 1970) that, under the most favourable circumstances, (notably high pore pressure and low adhesion), a sheet of this type, of thickness 10 km,is unlikely to have a total length from the leading edge to the junction with the mantle, of more than about 40 km. This is true unless the thrust sheet was actually moving down an incline assisted by gravity, a form of motion which seems incompatible with a direct connection with the mantle. For greater lengths the sheet will not slide but buckle, resulting in a thicker and shorter body giving rise to a much higher anomalous gravity field than that actually observed.

Butler also investigated, within the range of 8 to 13 km., the effect of varying sheet thickness. Although thicknesses of the order of that shown in cross section IOMA were not envisaged, extrapolation of the smooth thickness-length curves he obtained would suggest that this model is mechanically satisfactory, provided that the frontal parts of the sheet now eroded away did not make up a significant portion of its total original length. The situation is rather different in the case of cross section MUSA, which, as noted in Section 6.1, is probably more truly representative of the belt as a whole since there is little evidence for transcurrent disruptive faulting normal to the plane of the cross section. The overthrust in the MUSA model is only about 13 km. thick, i.e. within the range considered by Butler, and about 60 km long from mantle junction to outcrop. Since the fragment of ultramafic rock to the south of the Musa Valley was almost certainly once continuous with the belt to the north, the total original length was probably at least 100 km. Raleigh (1967) has shown that the weakening of serpentine during dehydration could have a significant effect on tectonic processes and,taking this into account, Butler's work suggests that a sheet of this nature is at the extreme limits of possibility, a conclusion which can hardly be said to give much support to the overthrust hypothesis.

An objection to the overthrust hypothesis may also be formulated on regional geological grounds; the Papuan Ultramafic Belt is only one of a series of major ultramafic bodies extending from Celebes through New Guinea and New Caledonia to New Zealand, the majority of which have been mapped as intrusives (Kündig, 1956; Visser and Hermes, 1954; Dow and Decker, 1963). Although in many cases this identification is a supposition based on texture and petrology, and not on observed field contacts, the development of the overthrust hypothesis for the origin of

the Papuan Ultramafic Belt has led at least some workers to consider and reject a similar schema for the areas with which they themselves are most familiar (Dow, pers. comm.). In particular overthrusting seems impossible in the case of the Marum Basic Belt and April Ultramafics of central New Guinea, whose tectonic position relative to the New Guinea Highlands closely resembles that of the Papuan Ultramafic Belt to the Owen Stanley Ranges, but which are separated from the oceanic areas to the north by a crust of continental thickness (Watts, 1969). No theory of origin of the Papuan ultramafics which completely ignores petrologically similar and apparently structurally related rocks can be described as satisfactory, yet a simple mantle overthrust seems possible only in the case of the New Caledonian massifs.

In view of the difficulties raised by the concept of tectonically emplaced oceanic crust and upper mantle, other suggestions that have been made seem worth considering. A simple intrusion, even if emplaced in its present position by subsequent thrusting, seems unlikely; not only have no intrusive contacts been observed except within the belt itself, but the mass is notably asymmetric, layered from coarse grained ultramafic to fine grained mafic, and much of this uppermost unit displays the pillow textures characteristic of extrusive rocks. The plutovolcanic hypothesis, which assumes extrusion, presents no problems for the gravity analyses, since, as pointed out in Section 6.3, models in which the ultramafics are assumed to be terminated or very greatly attenuated at depth can satisfactorily be fitted to the observed fields, but has been criticised and rejected by a number of authors (Vuagnat, 1963; Kaaden, 1964; Thayer, 1967, 1969). Their objections have been conveniently summarised under five headings by Davies (1969):

"1. The typical ophiolite sequence is bottom heavy, with too much ultramafic differentiate for the volume of associated gabbro.

2. If the parent magma had been basaltic there should be a fraction enriched in Fe, Na and K to provide a chemical counter-weight for the Ca-Mg-rich ultramafic fraction.

3. The extrusion of a tongue of lava of such great volume at one time is unlikely.

4. Field evidence for a complete envelope of basalt and dolerite enclosing the plutonic rocks has not been established.

5. The gabbro-peridotite contact, instead of being transitional, is commonly intrusive, gabbro into peridotite."

It is apparent that the first two, at least, of these objections are valid only if it is a necessary condition that the magma extruded be of overall basaltic composition. The term 'basaltic (simatic)' was admittedly used by Aubouin, but his illustration, reproduced here as Figure 7.2, clearly implies a primary composition very far from that usually accepted as such. The basalt assumption has been made partly because of the observed lack of thermal metamorphism at ophiolite contacts, despite the high melting points of peridotites and pyroxenites, partly because of the apparent impossibility of raising such large masses of ultramafic rock, denser than normal upper crustal rocks even when in the fluid state, against isostatic forces, and partly because of the lack of proven cases of current or recent ultramafic extrusive activity. The third point is the most easily answered, since the conditions postulated by Aubouin are confined to regions (the undersea margins of geosynclines) difficult to observe in practice, and since in addition the ultramafic core of any such extrusions would be

exposed only after faulting or prolonged erosion. The second point can be countered by noting that virtually all observed ophiolite contacts are tectonic, and that primary igneous interfaces have not been definitely identified. Moreover the ultramafic component of the intrusion is always shown as existing only under a thermally insulating carapace of solidifying basaltic and gabbroic differentiate. It is not even necessary to suppose that the ultramafics were entirely liquid during extrusion since the gabbroic intrusives in the upper parts of the peridotite may be former interstitial liquids in an olivine-pyroxene crystal mush able to move as a high viscosity fluid. Davies (1969) divides the ultramafic rocks of the Papuan Ultramafic Belt into non-cumulus and less common cumulus members, the former possibly being the final solidification product of such a mush and the latter a true cumulate from the interstitial fluid and low melting point fraction.

Theoretical difficulties due to the apparently anti-isostatic emplacement of magmas arise not only with ophiolites but even with large layered gabbroic intrusions; Rast (1970), in a general review of the subject, has proposed what he terms the volumetric expansion mechanism, wherein the magma is seen as rising from the asthenosphere because of expansion associated with phase changes or partial melting within the mantle. A process of this sort appears to be taking place at the mid-ocean ridges and results in the continuous production of fresh ocean floor. However the very rugged bathymetry of the crestal zones of these ridges suggests that they are loci primarily of intrusion, and that extrusive flows, if they occur at all, do not travel far. However if, as suggested by Karig (1970), similar rifting can take place at trench margins, then the greater depth of the asthenosphere would allow expansion effects to be important over a much greater length of the rising column, which might then flow out over

the crust as a massive extrusion. On this view the similarity in petrology between the ophiolite suite and rocks dredged from the deep ocean floors is due not to ophiolites being infaulted slabs of preformed oceanic crust but to their very similar mode of origin. Moores (1969, p. 60) notes that the true oceanic conditions were apparently never involved in ophiolite formation, and also that "the development of fault bounded troughs immediately prior to ophiolite emplacement" would imply that the masses were emplaced in an extensional tectonic environment.

Models for the Papuan Ultramafic Belt which imply extension have the merit of being consistent with the models fitted to the gravity profiles further east; in particular the apparently abrupt termination of the main belt in Collingwood Bay and the dispersion of possibly related bodies throughout the D'Entrecasteaux Islands and on the Cape Vogel Peninsula further east seems simply explicable in terms of rift bifurcation. Although he does not discuss mechanisms, Moores (1969) essentially accepts the plutovolcanic hypothesis as providing the best explanation for the observed field relationships of the Vourinos Massif, specifically rejecting, as does Davies (1969), Thayers' (1967) contention that the fine grained rocks are not integral parts of the ophiolite complex. Control of ophiolite emplacement under tension obviously provides scope for the observed variation from dominantly extrusive to dominantly intrusive bodies along the same tectonic lineation in the south-west Pacific.

The present structural position of the Papuan Ultramafic Belt, and probably of the New Caledonian 'grands massifs', as overthrusts necessitates only one further, relatively simple, movement. Aubouin (1965) argues that extrusion of ophiolites takes place on the geanticlinal ridge; this is a position of considerable gravitational instability, so that even after solidification any weakness in or near the basal plane would allow

gravity sliding of the entire block over sediments deposited within the geosynclinal trough. Such a process would account for the absence in many cases of field evidence for a complete basaltic envelope, although it appears that in Eastern Papua the remnants of just such an envelope may crop out in the Owen Stanley Fault Zone, where modelling for profile IOMA proved simplest with a polygon of high density rock extending to considerable depth.

Of the objections listed by Davies (1969) only the third, that "the extrusion of a tongue of lava of such volume at one time would seem unlikely", has not been so far discussed; it is perhaps sufficient to note that similar volumes were probably involved in individual flows of plateau basalt, whose low viscosity resulted in solidification in sheet-like rather than podiform masses, and also that the situations in which ophiolites are found are sufficiently restricted for relatively improbable mechanisms to be reasonably invoked.

It is not the purpose of this thesis to discuss the larger question of the nature of geosynclines, whether tensional rifts analogous to the Red Sea, zones of crustal absorption similar to the Tonga Trench or, as suggested by Karig's (1970) work, complex combinations of the two. The hypothesis outlined here is simply that Eastern Papua was originally a depression filled with sediments and volcanics marginal to the Australian continent, from which it has since been separated by triangular rifting. Such rifting in the New Guinea area has formed both the Coral and Solomon Seas and is currently enlarging the Woodlark Basin at the expense of the latter. The basis for this suggestion is found in the seismic and bathymetric data discussed in Chapter 5, coupled with the difficulty found in reconciling the observed gravity field of the Papuan Peninsula with the previously proposed compressional (mantle overthrust) hypothesis. It must be emphasised that the gravity data and mechanical

calculations are still very far from disproving the overthrust, and it can only be said that, on the evidence now available, the balance of probabilities appears to favour the pluto-volcanic hypothesis.

It is hoped that the discussion presented here may stimulate further work in two directions in particular; firstly into the mechanical and thermal conditions which would permit ophiolite extrusions of the type suggested, and secondly in the search for confirmation of the proposed extensional movements in the remainder of New Guinea and in New Britain.

ACKNOWLEDGEMENTS

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A P P E N D I X A

The derivation of the isothermal barometric equation is given in a number of text books. However less attention appears to have been paid to the lapse rate formula and a simple comparison could not be found in the course of a literature search. The discussion below is perhaps worth reproducing for these reasons.

Dry air is assumed to behave as a perfect gas, i.e.

(1) $p = \rho r\theta$, where p is the pressure at a point in a gas, ρ and θ the corresponding density and temperature and r the appropriate gas constant.

Now in a column of air in equilibrium the weight of the gas is supported by the pressure difference, i.e.

(2) $dp/dh = -\rho g$ and substituting for ρ from equation (1)

(3) $dp/p = -g\, dh/r\theta$

Intergration of this equation gives the relation between pressure and height. For an isothermal atmosphere θ is constant.

$$\int_{p_o}^{p_1} \frac{dp}{p} = \frac{g}{r\theta} \int_{h_o}^{h_1} dh$$

(4a) $\log\left(1 + \frac{\Delta p}{p}\right) = -\frac{g}{r\theta} h$ where $h = h_1 - h_o$ and $\Delta p = p_1 - p_o$

For an atmosphere with a uniform lapse rate $\theta = \theta_o - sh$ where s is the lapse rate.

$$\int_{p_o}^{p_1} \frac{dp}{p} = -\frac{g}{r} \int_{h_o}^{h_1} \frac{dh}{(\theta_o - sh)}$$

(4b) $$\left(1 + \frac{\Delta p}{p_o}\right)^{\frac{rs}{g}} = 1 - \frac{sh}{\theta_o} \quad \text{putting } h_o = 0$$

Equation 4(a) may be expanded using the log series and 4(b) using the binomial expansion (Δp being always less than p_o). Putting $\Delta p/p_o = x$, for the isothermal case:-

(5a) $$-gh/r\theta_o = x - x^2/2 + x^3/3 - x^4/4 \ldots.$$

and with a uniform lapse rate

$$1-sh/\theta_o = 1 + \frac{rs}{g}x + \frac{rs}{2g}\left(\frac{rs}{g}-1\right)x^2 + \frac{rs}{6g}\left(\frac{rs}{g}-1\right)\left(\frac{rs}{g}-2\right)x^3 + \frac{rs}{24g}\left(\frac{rs}{g}-1\right)\left(\frac{rs}{g}-2\right)\left(\frac{rs}{g}-3\right)x^4 \ldots$$

in both cases ignoring terms higher than x. Since $\Delta p/p$ will seldom exceed .2 this is reasonable. The factor rs/g will have a value of about .2, so mixed terms of the fourth power may also be ignored. The lapse rate equation then becomes

$$(5b) \quad -gh/r\theta_o = x - \tfrac{1}{2}x^2 + {}^1/_3 x^3 - {}^1/_4 x^4 + \tfrac{1}{2}\frac{rs}{g}(x^2 - x^3)$$

In both these expressions θ_o is assumed to be the temperature measured at ground level. The ground temperature can be used to obtain a mean air column temperature, $\theta_o - \frac{1}{2}sh$, and substituting this in the Isothermal formula we have

$$-gh = r(\theta_o - \tfrac{1}{2}sh)(x - \tfrac{1}{2}x^2 + {}^1/_3 x^3 - {}^1/_4 x^4) \text{ or } -gh = r(\theta_o - \tfrac{1}{2}sh)I$$

where $I = x - \frac{1}{2}x^2 + {}^1/_3 x^3 - {}^1/_4 x^4$

Substituting again for h on the right hand side gives

$$-gh/r = \theta_o I + \tfrac{1}{2}rs\ (\theta_o I - \tfrac{1}{2}sh\,I)\,I/g$$

The term $\frac{1}{2}rs \cdot \frac{1}{2}sh \cdot I^2/g$ will involve, as the term of lowest power

$$\left(\frac{rs}{g}\right)^2 \left(\frac{\Delta p}{p_o}\right)^3$$ and may therefore be neglected i.e.

$$-\frac{g}{r}h = \theta_o I + \tfrac{1}{2}\frac{rs}{g}\theta_o I^2$$

and again neglecting terms higher than the fourth power

$$-\frac{g}{r}h = \theta_o I + \frac{1}{2}\frac{rs}{g}\theta_o (x^2 - x^3)$$

which is identical with the lapse rate formula. Hence, if the true mean temperature of the air column is used, the isothermal formula is no less accurate than the uniform lapse rate formula.

APPENDIX B

TERRAIN CORRECTIONS, HAMMER ZONES D TO H, FOR SELECTED STATIONS

Station No.	Description	'Topographic'	'Bathymetric'
6701-0273	On the south coast of Misima, approximately 1 mile from Mt. Oiatau. Very steep terrain and a sharply shelving coast. Approximately half the included area marine.	19.9	1.7
6701-0035	In the centre of the mountainous part of Goodenough Island. All the included area very rugged.	12.2	-
6808-0049	In the centre of the mountainous part of the East Cape Peninsula, north of Alotau. All the included area, except for a small coastal strip in the south, very rugged.	9.7 (8.8)	-
6701-0055	In the southern part of the Bwebweso block on Normanby Island, at one of the highest points. The included area contains the very steep south face of the block.	7.9	
6701-0078	In the eastern part of the Mailolo block in north-west Fergusson Island, at a low point in the range. The included area is typical of 'Owen Stanley' type terrain.	7.6 (6.9)	
6701-0056	On top of Mt. Bwebweso (Normanby Island). The terrain effect at this station increases markedly towards the outer zones.	7.4	
6808-0007	In the valley of the Saga-Aho river, south-eastern mainland. Terrain typical of the 'basaltic' mountains.	5.8	
6701-0544	On the Kutu river inland from Wedau. The station is in a fairly wide, braided river course, surrounded by 'basaltic' mountains to 3000'.	5.7	

Station No.	Description	'Topographic'	'Bathymetric'
6701-0075	In a river valley in the centre of the south-eastern mountain block on Fergusson Island. Typical 'Owen Stanley' type terrain.	5.3	
6701-0040	At the junction of the mountains and the coastal plain on Goodenough Island. About half of the included area is very rugged.	4.8	
6808-0124	In the rugged basaltic mountains behind Nowata airstrip. The station is at roughly the mean height for the area.	2.8 (3.4)	
6701-0086	In moderately rugged terrain on the north flank of the south-western mountain block, Fergusson Island.	2.3	
6808-0028	In the middle of the 'spine' of north-west Normanby Island. The corrections are only significant close to the station.	2.0	
6701-0254	On the south coast of Sariba Island. The marine part, rather more than half of the included area, lies entirely within the barrier reef. The terrain is very steep close to the station.	1.7	
6701-0493	Near the southern edge of the mountainous part of the south-east mainland, in a broad stream valley.	1.4 (1.5)	
66.5-0264	In a stream draining the Cape Nelson volcanoes about one third of the way into the mountains.	1.1	
6701-0381	In the centre of the hilly part of eastern Misima.	.9 (1.2)	
6808-0146	On the Cape Vogel peninsula, western end.	.9	
6808-0162	On the Cape Vogel peninsula, eastern end.	.9	

Station No.	Description	'Topographic'	'Bathymetric'
6701-0160	On the north coast of Gawa Island. About three fifths of the included area is marine, two fifths beyond the fringing reefs.	.5	.1
6701-0475	On the south coast of Bapua, near Baxter Harbour. About three fifths of the area is marine, but within the Barrier reef.	.1	.1
6701-0401	On small island in the Calvados chain close to the edge of the Barrier reef.		1.3
6701-0300	On small island in the Calvados chain, in the middle of the area enclosed by the Barrier reef.		.4
6701-0188	In Lachlans, all the included area either emergent or within the reef.		.3
6701-0021	On the Killerton Islands, on the north side of Milne Bay.		.1

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EASTERN PAPUA

SMOOTHED FREE AIR ANOMALIES
½° FILTER. CONTOUR INTERVAL 10 MILLIGALS

10 5 0 10 20 30 40 50 miles

TRUST TERRITORY OF NEW GUINEA
TERRITORY OF PAPUA

BRITISH SOLOMON ISLANDS PROTECTORATE

CORAL SEA

SOLOMON SEA

PORT MORESBY

WAU

OPOMETTA

GOODENOUGH I.

FERGUSSON I.

NORMANBY I.

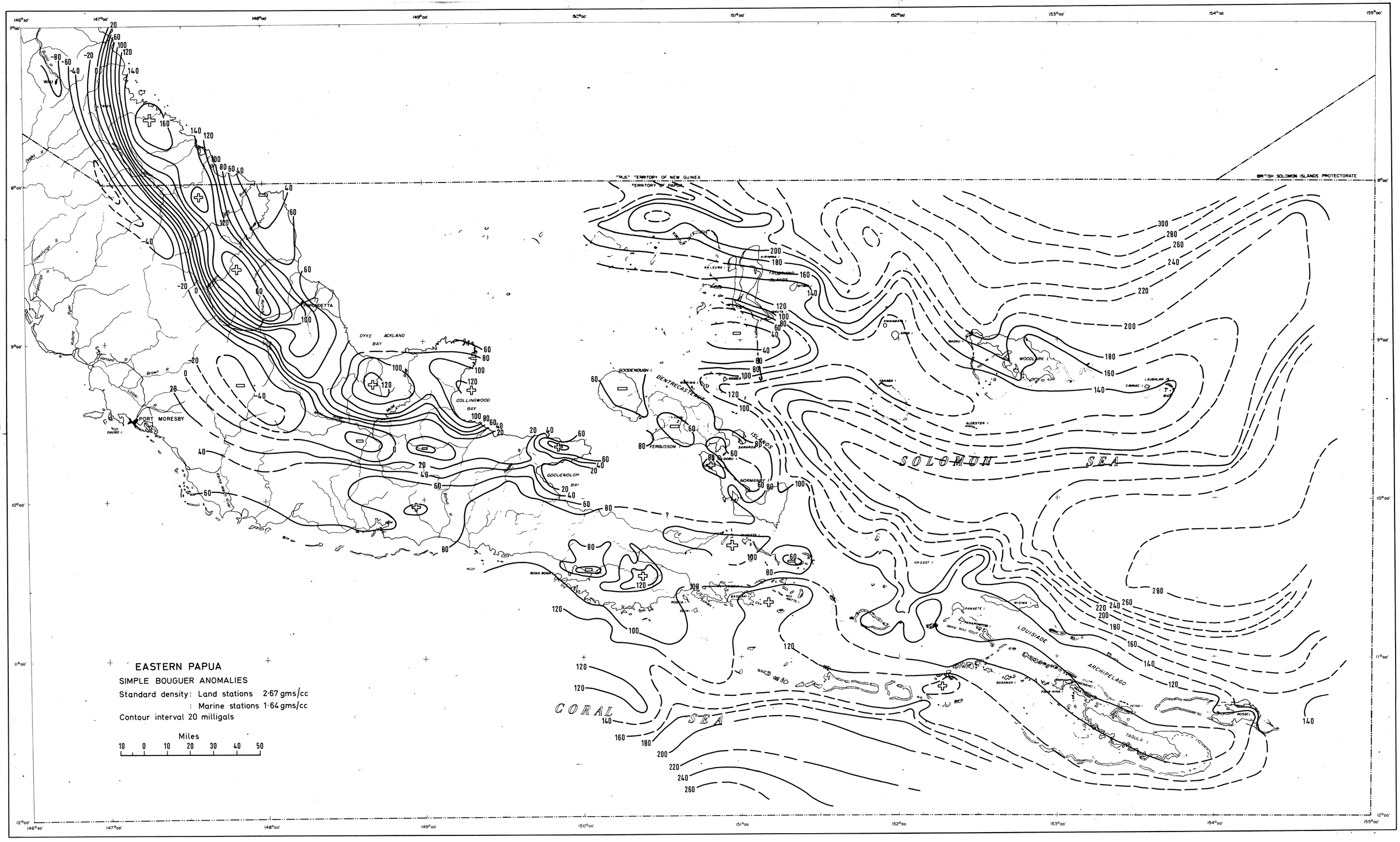
WOODLARK I.

LOUISIADE ARCHIPELAGO

TAGULA I.

BASSEL I.

7°00'
8°00'
9°00'
10°00'
11°00'
12°00'
146°30'
147°00'
148°00'
149°00'
150°00'
151°00'
152°00'
153°00'
154°00'
155°00'


146°30'
147°00'
148°00'
149°00'
150°00'
151°00'
152°00'
153°00'
154°00'
155°00'
7°00'
8°00'
9°00'
10°00'
11°00'
12°00'
TRUST TERRITORY OF NEW GUINEA
TERRITORY OF PAPUA
BRITISH SOLOMON ISLANDS PROTECTORATE
PORT MORESBY
HOSKINS AERODROME
DYKE ACKLAND BAY
COLLINGWOOD BAY
GOODENOUGH BAY
BONA BONA
DENTRECASTEAUX
TROBRIAND ISLANDS
WOODLARK I.
LOUISIADE ARCHIPELAGO
SOLOMON SEA
CORAL SEA
Fly R.
Strickland R.
Bosavi R.
Kikori R.
Purari R.
Vanapa R.
Brown R.
Laloki R.
Goldie R.
Musa R.
Mambare R.
Kumusi R.
Waria R.
Lakekamu R.
Opi R.
Kemp Welch R.
Bonga R.
Angabanga R.
Gira R.
Lilley R.
Kwaiawata R.
Dawson Str.
Moresby Str.
Basilaki I.
Normanby I.
Fergusson I.
Goodenough I.
Sariba I.
Kaileuna I.
Kiriwina I.
Iwa I.
Gawa I.
Kwaiawata I.
Vanaba I.
Madau I.
Woodlark I.
Laughlan Is.
Cannac I.
Alcester I.
Sanaroa I.
Dobu I.
Rossel I.
Misima I.
Panaeati I.
Panapompom I.
Bagaman I.
Panaeati I.
Tagula I.
Rossel I.
Yela I.
EAST I.
EASTERN PAPUA
SIMPLE BOUGUER ANOMALIES
Standard density: Land stations 2·67 gms/cc
: Marine stations 1·64 gms/cc
Contour interval 20 milligals
Miles
10 0 10 20 30 40 50

TRUST TERRITORY OF NEW GUINEA
TERRITORY OF PAPUA

BRITISH SOLOMON ISLANDS PROTECTORATE

CORAL SEA


SOLOMON SEA

EASTERN PAPUA
EXTENDED BOUGUER ANOMALIES

Contour interval 10 milligals

10 0 10 20 30 40 50 miles

Extended Bouguer Anomalies
Variable onshore density
Marine areas corrected using
ρ = 2·67 gms/cc


EASTERN PAPUA
AIREY ISOSTATIC ANOMALIES
T = 30 km
Contour interval 20 milligals
10 0 10 20 30 40 50 miles
146°30'
147°00'
148°00'
149°00'
150°00'
151°00'
152°00'
153°00'
154°00'
155°00'
7°00'
8°00'
9°00'
10°00'
11°00'
12°00'
TRUST TERRITORY OF NEW GUINEA
TERRITORY OF PAPUA
BRITISH SOLOMON ISLANDS PROTECTORATE
WAU
Bulolo R
PORT MORESBY
DAUGO I.
POPONDETTA
DYKE ACKLAND BAY
COLLINGWOOD BAY
GOODENOUGH BAY
GOODENOUGH I.
FERGUSSON I.
NORMANBY I.
SANAROA I.
D'ENTRECASTEAUX ISLANDS
TROBRIAND ISLANDS
KITAVA I.
KWAIAWATA I.
GAWA I.
MADAU I.
WOODLARK I.
LAUGHLAN IS
CANNAC I.
ALCESTER I.
YANABA I.
EAST I.
NUAKATA I.
SIDEIA I.
BASILAKI I.
WATTS I.
ROGEIA I.
SARIBA I.
DOINI I.
BONA BONA I.
PANAETE I.
PANAPOMPOM I.
MISIMA
BAGAMAN I.
PANA-WINA I.
PANA TINANI
YEINA I.
TAGULA I.
ROSSEL
LOUISIADE ARCHIPELAGO
SOLOMON SEA
CORAL SEA
Vanapa R
Brown R
Laloki R
Kemp Welch River
Musa River
Mambare
Kumusi
Gira River
Bonua R
Inawafunga R
Angabunga R
Kubuna River
Oreba R
200
180
160
140
120
100
80
60
40
20
0
-20
-40

TRUST TERRITORY OF NEW GUINEA
TERRITORY OF PAPUA

BRITISH SOLOMON ISLANDS PROTECTORATE

SOLOMON SEA

CORAL SEA

PORT MORESBY

POPONDETTA

WAU

TROBRIAND ISLANDS

DENTRECASTEAUX ISLANDS

LOUISIADE ARCHIPELAGO

DYKE ACKLAND BAY

COLLINGWOOD BAY

GOODENOUGH BAY

KALEUNA I.

KIRIWINA I.

ISTAVA I.

WOODLARK I.

LAUGHLAN IS

CAMAC I.

ALOTAU

GOODENOUGH I.

FERGUSSON I.

NORMANBY I.

DOBU I.

SAMARAI I.

ROSSEL I.

TAGULA I.

SUDEST I.

PNG/B2-36

BASED ON PNG/80-28

S-E PAPUA & NEW GUINEA
GRAVITY STATIONS

MILES
10 0 10 20 30 40 50

BATHYMETRIC CONTOURS IN METRES